FINAL REPORT

FREIGHTLINER LLC
A DaimlerChrysler Company

Electronically Controlled Braking Systems (ECBS) Intelligent Vehicle Initiative Field Operational Test

Combined Templates 2 and 3:
Mixed and Optimized Tractor-Trailer

Cooperative Agreement DTFH61-02-X-00096

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EXECUTIVE SUMMARY

As one part of its thrust to reduce large truck-related fatalities, the United States Department of Transportation (DOT) is working closely with the trucking industry to promote voluntary deployment of advanced safety technologies that can reduce fatal crashes of commercial motor vehicles (CMVs). Several heavy commercial vehicle research programs sponsored by the DOT have been focused on testing and evaluating the effectiveness of intelligent vehicle technologies to reduce rear-end collisions, lane departures, rollovers, understeer and oversteer (yaw) instabilities, and lane change/merge crashes.

In 2003, the DOT contracted with a team led by Freightliner LLC to undertake the *Field Operational Test of Electronically Controlled Braking Systems (ECBS)* to collect field data needed to demonstrate the benefits of onboard electronic safety systems in a real-world operating environment. In parallel, the DOT contracted with Booz Allen Hamilton to serve as the independent evaluator (IE) for the field test, i.e., to analyze the data collected by the conductor team.

The overall goal of the DOT related to the ECBS Field Operational Test (FOT) was to develop and demonstrate an improved understanding of ECBS and its enabled technologies in terms of performance, reliability, durability, maintainability, and safety benefits in a real-world operating environment. The DOT structured the program around “templates,” each designed to examine different aspects of the performance of ECBS and its enabled technologies:

The Freightliner Team was selected to conduct the Template 2 and Template 3 FOT with the specific objectives to design, implement, and conduct the FOT to collect data needed by the IE and to demonstrate to truck fleets that these systems are reliable and can improve productivity.

The conductor team was led by Freightliner LLC and included Meritor WABCO (MW), Bendix Commercial Vehicle Systems LLC (BDX), Wal★Mart[1], Battelle, the U.S. Army Aberdeen Test Center, with support from General Electric TIP, Great Dane Trailers, and Hendrickson.

[1] Wal★Mart® is a registered trademark of Wal-Mart Stores, Inc.

The primary technology being investigated in this FOT was ECBS on tractors and trailers. ECBS of both major manufacturers of brakes for Class 8 tractors and semi-trailers, Meritor WABCO and Bendix, were evaluated. In addition, several other braking technologies were present on some of the vehicles in the study:

- Next-generation antilock braking systems (ABS),
- Adaptive cruise control (ACC) with active braking on tractors,
- Yaw stability control on tractors, and
- Roll stability control (RSC) on tractors and trailers.

In addition to these electronic safety systems, the Freightliner Team also included air disc brakes (ADB) in select vehicles to capture critical information on the compatibility of ADB when mixed and matched with conventional drum brakes.

The Freightliner Team conducted the two templates in parallel in a Wal★Mart fleet operating out of the Loveland, Colorado, distribution center. A total of 48 instrumented Freightliner Columbia tractors and 100 instrumented Great Dane trailers participated in the combined templates for 12 months.

- In Template 2, the Team fielded 40 tractors and 60 trailers in four configurations. Template 2 was designed to examine issues of compatibility of different systems on tractors and trailers, i.e., compatibility and performance of tractors and/or trailers equipped with ECBS matched (married) with tractors and/or trailers equipped with ABS or ECBS from different vendors, and
- In Template 3, the Team fielded eight tractors and 40 trailers with Meritor-WABCO ECBS and advanced technologies. Template 3 was designed to examine issues of performance and reliability of matched or optimized systems in which both tractor and trailer were equipped with ECBS technology as well as enabled safety technologies such as ACC, stability control, and roll stability for tractors and trailers.

In the day-to-day product delivery operations of Wal★Mart's Loveland distribution center, tractors returned to the base terminal upon completion of their local trips, and the geographic span of the field test was a defined area of Colorado and surrounding states, including a wide variety of routes and terrain.

In the first part of the program, the Freightliner Team focused on planning and working out the design and strategy for the program in collaboration with the DOT and the IE. The Freightliner ECBS FOT Test Plan (Freightliner 2005) was developed, which provided a detailed outline of the tests and work to be conducted to prepare the vehicles for the field test as well as to conduct the FOT.

In the second part of the program, the Freightliner Team dedicated its efforts to conducting the field test, including training of drivers and technicians, release of instrumented vehicles to Wal★Mart, data collection for 12 months, FOT logistics management, and the reporting phases of the program.

The Freightliner Team collected onboard driving data, maintenance and operational records, and the opinions of drivers and mechanics.

- Over 4 million miles of onboard driving data relevant to brake system performance and safety-related vehicle dynamics were recorded continuously at 10 Hz on both tractors and trailers throughout the FOT. A total of 68 channels of data were collected from the vehicle data buses (e.g., Society for Automotive Engineers, or SAE J1939 data bus), analog sensors (e.g., pressure transducers), and digital inputs (e.g., headlights), providing information on vehicle dynamics, system performance, driving environment, and driver behavior
- Maintenance records related to brake systems and tires were also obtained by the Freightliner Team and provided to the IE for use in estimating the reliability, performance, and costs associated with the new technologies in comparison to conventional technologies.
- Surveys of drivers and mechanics were conducted before, during, and after the FOT to seek opinions on the reliability, maintainability, and safety impacts of the new systems.

Upon completion of the FOT data collection, the DAS units and other instrumentation were removed from the vehicles.

The research program benefited the trucking industry and the general public by advancing technologies that have a potential to enhance safety on our nation’s highways. Substantial field data and experience were obtained on performance, reliability, maintainability, durability, compatibility, and safety of ECBS, related enabled technologies, and ADB in real-world environments:

- Forty-eight (48) tractors and one hundred (100) trailers were outfitted with various combinations of standard production and preproduction brake and safety systems including ECBS, next-generation ABS, ACC, roll stability technologies, yaw stability technologies, and ADB
- The tractors and trailers were successfully fielded for 12 months in a normal operating environment
- ECBS, enabled technologies, and ADB integrated on the tractors and trailers functioned with no major interruption or failure in several million miles and nearly 2 years of service
- Technologies were activated in stages during the data collection period, and the enabled technologies were implemented successfully
- No incompatibility of advanced technology tractors or trailers with conventional tractors or trailers was observed in several million miles and nearly 2 years of service
- Over 4 million miles of engineering data were collected onboard the tractors and trailers
- Maintenance operations of the fleet were recorded on the tractors and trailers for the duration of the FOT, i.e., from the date the vehicles were placed in service to the end of data collection, totaling 22 months of operation
- Opinions of 34 technicians and 40 drivers were obtained
- The Wal★Mart fleet, its drivers, and mechanics reported being satisfied with the performance of the tractors and trailers.

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ABBREVIATIONS AND GLOSSARY

ABS	Anti-lock brake system(s)
ACC	Adaptive cruise control
ADB	Air disc brakes
ATA	American Trucking Associations
ATC	Automatic traction control
BDX	Bendix Commercial Vehicle Systems LLC (Bendix)
BPM	Brake performance monitoring
CCC	Conventional cruise control
CMV	Commercial Motor Vehicle
CSV	Comma Separated Value
CWS	Collision warning system
DAS	Data acquisition system
DOT	United States Department of Transportation (see also USDOT)
DVD	Digital versatile disc
ECBS	Electronically controlled brake system(s)
ECU	Electronic control unit
ESC	Electronic stability control
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standards
FOT	Field operational test
FTP	File transfer protocol
GPS	Global positioning system
IE	Independent evaluator
I/O	Input/output
IRB	Institutional review board
LWC	Lining wear control
LWS	Lining wear sensing
LWS&C	Lining wear sensing and control
MW	Meritor WABCO

NHTSA	National Highway Traffic Safety Administration
PCMCIA	Personal Computer Memory Card International Association
RFA	Request For Application
RO	Repair order
RSC	Roll stability control
RSS	Roll stability support
SAE	Society of Automotive Engineers
T2	Template 2
T3	Template 3
T2C1	Template 2 Configuration 1
T2C2	Template 2 Configuration 2
T2C3	Template 2 Configuration 3
T2C4	Template 2 Configuration 4
T3	Template 3
TCV	Trailer control valve
TEBS	Trailer electronic braking system
TMC	Truck Maintenance Council
TRSP	Trailer Roll Stability Program™
VIN	Vehicle identification number
VMT	Vehicle miles traveled
VMRS	Vehicle Maintenance Reporting System
USDOT	United States Department of Transportation

FINAL REPORT

Electronically Controlled Braking Systems (ECBS) Intelligent Vehicle Initiative Field Operational Test

Combined Templates 2 and 3: Mixed and Optimized Tractor-Trailer

1.0 INTRODUCTION

1.1 Background

According to Federal Motor Carrier Safety Administration (FMCSA) statistics, “of the people killed in motor vehicle crashes in 2004, 12 percent (5,190) died in crashes that involved a large truck” (FMCSA 2003). Another 116,000 people were injured in crashes involving large trucks. Only about 15 percent of those killed and 23 percent of those injured were occupants of large trucks (NHTSA 2005). The fatality rate in 2004 was 2.16 fatalities per 100 million miles, representing a decrease of 16.9 percent since 1997. Nevertheless, a priority goal of FMCSA is to further reduce the large truck-related fatality rate to 1.65 per 100 million truck-miles by the year 2008 (Sandberg 2003).

To help reduce large truck-related fatalities, the United States Department of Transportation (DOT) is working closely with the trucking industry to promote the voluntary deployment of advanced safety technologies that can reduce fatal crashes of commercial motor vehicles (CMVs). Over more than 8 years, several intelligent vehicle technologies have been tested to determine their effectiveness to reduce crashes. These advanced technologies have focused on advanced braking systems, lane departure warning systems, roll advisors and controllers, and collision warning devices. In the area of heavy vehicles, DOT is specifically focusing its efforts on systems that can reduce rear-end collisions, lane departure, rollover, understeer and oversteer (yaw) instability, and lane change/merge collisions.

Electronic onboard safety systems offer significant promise in reducing accidents because they can sense an impending crash and react more quickly than can the most experienced drivers. Electronically controlled braking systems (ECBS) provide an enabling platform for systems that support controlled braking and vehicle stability in an impending crash and reduce the likelihood of instability crashes such as rollover or jackknife. Fortunately, implementing electronic safety systems on truck platforms to improve CMV safety is achievable on a broad scale. However, commercial motor carriers operate on tight profit margins and need data on reliability, performance, benefits, and costs of technologies before they will embrace and implement these systems. The DOT also needs safety benefits data that demonstrate the reduction in crashes, fatalities, and injuries offered by these systems to support policy changes that encourage their adoption. In the autumn of 2002, the DOT issued a request for applications (RFA) to undertake a field operational test (FOT) to demonstrate electronic safety technologies such as ECBS and to collect critical performance data to support the adoption of such technologies (USDOT 2002). In 2003, a team led by Freightliner LLC was selected and contracted under Cooperative Agreement Number DTFH61-02-X-00096 to undertake the *Field Operational Test of Electronically Controlled Braking Systems (ECBS)* to collect needed data to demonstrate the benefits of onboard electronic safety systems in a real-world operating environment. In parallel, the DOT contracted with Booz Allen Hamilton to serve as the independent evaluator (IE) for the field test to analyze the data collected by the conductor team.

Freightliner LLC assembled its team, including Meritor WABCO, Bendix Commercial Vehicle Systems LLC, Wal★Mart, Battelle, and the U.S. Army Aberdeen Test Center, with support from General Electric TIP, Great Dane Trailers, and Hendrickson, to develop and demonstrate an improved understanding of the following safety technologies:

- ECBS on tractors and trailers
- ECBS-based and ABS-based adaptive cruise control (ACC) on tractors with active braking
- Yaw stability control on tractors
- Roll stability control (RSC) on tractors and trailers
- Air disc brakes (ADB) on tractors and trailers.

The Team conducted two parallel tests or "templates"[2] operating from a Wal★Mart distribution center in Loveland, Colorado. The two FOT templates were:

- Template 2: Mixed Tractor-Trailer, which fielded 40 Freightliner tractors and 60 Great Dane trailers to evaluate the compatibility and performance of tractors and trailers equipped with different braking systems.
- Template 3: Optimized or Matched Tractor-Trailer, which fielded eight Freightliner tractors and 40 Great Dane trailers to evaluate tractor-trailer combinations equipped with ECBS (from the same manufacturer) and advanced safety systems enabled by ECBS, including ACC with active braking, electronic stability control (ESC), and roll stability support (RSS).

This large FOT focused on improving the understanding of safety system technologies in terms of their performance, reliability, durability, maintainability, and safety benefits in a real-world operating environment. Data were collected in these FOT templates first with the systems turned off, and then with the systems turned on, to compare safety benefits in terms of mitigating near-crash or degraded situations. The Freightliner Team provided the data to the DOT and its IE for detailed analyses. Three types of data were collected:

- Driving data, relevant to brake system performance and safety-related vehicle dynamics, recorded continuously onboard the vehicles
- Fleet maintenance data, for use in evaluating reliability, performance, and costs associated with the new technologies
- Surveys to capture opinions of drivers, mechanics, and operators on the performance, reliability, and maintainability of the new systems.

The program was originally focused on ECBS and its enabled technologies, but was expanded to include other brake technologies, such as new-generation ABS systems and disc brakes. The brake technologies evaluated by this program are described in Section 2.0 of this report.

[2] The DOT proposed three tests or "templates" in its RFA for this program. The Freightliner Team was selected to conduct Templates 2 and 3. The original Template 1 was not funded.

This document is the final report of the Freightliner-led conductor team for the FOT. It provides a summary of activities during the design, preparation, and implementation phase of the program as well as the outcomes of the field test. It includes summaries of the technologies under evaluation, as well as many details related to conducting a large-scale FOT including data collection, data management, and data validation. The analysis of the data collected is beyond the scope of this report; it will be performed and reported separately by Booz Allen Hamilton, the IE for this FOT.

1.2 Goal and Objectives

The overall goal of the ECBS FOT is to develop and demonstrate an improved understanding of ECBS and its enabled technologies in terms of performance, reliability, durability, maintainability, and safety benefits in a real-world operating environment. The data and results generated by this program are intended to provide both the DOT and the commercial trucking industry with the information needed to make well-informed decisions concerning the performance and benefits of these technologies.

Table 1-1 details the objectives of the ECBS FOT program specified by the DOT in its RFA. A primary intent of the FOT was to gather data to evaluate and demonstrate the safety benefits of these technologies in support of DOT's mission to promote safety of vehicles operating on our nation's highways. Consequently, the DOT set out to show that the systems provide safety benefits to support their broader implementation.

In addition, a critical element of the program was to demonstrate to truck fleets that these systems are reliable and can improve productivity. While the trucking industry supports safety improvements, truck fleets operate on tight profit margins and are reluctant to try new technologies until they are convinced of both economic and safety benefits. Fleet operators want to see results from one of their fellow fleets that has tested and evaluated new systems and confirmed the systems are reliable and beneficial.

Table 1-1. DOT Objectives for the Freightliner Team ECBS FOT

Objectives of the original solicitation for the DOT ECBS FOT		Template 2	Template 3
Objective 1	To evaluate the **overall safety of ECBS in terms of performance, reliability, maintainability, and durability** in a variety of real-world environments by collecting real-time braking event data and collecting additional information from brake technicians and drivers.	●	●
Objective 2	To evaluate **the safety benefits of ECBS** in terms of mitigating near crash or degraded situations for systems **with advanced brake safety system components**.	●	●
Objective 3	To identify issues that affect the **suitability of ECBS** technology in an over-the-road, revenue-generating environment by documenting any problems or fault codes with the systems, as well as the frequency and circumstances of ECBS failures that would result in braking control being "switched" to the backup pneumatic system.	●	●
Objective 4	To assess the **maintainability** of ECBS relative to scheduled and unscheduled maintenance requirements, mechanic skill level impacts and/or ability to diagnose and resolve problems.	●	●
Objective 5	To document **driver information/experiences resulting from ECBS use**, focusing on driver acceptance, feedback related to system use, and behavior change.	●	●
Objective 6	Evaluate the **compatibility of tractor and trailer** ECBS from different vendors with conventional ABS.	●	
Objective 7	To evaluate the **overall performance and reliability of "optimized" ECBS** technology for tractor/trailer combinations where both tractor and trailer have ECBS with advanced safety features such as a high-speed network.		●

The program's templates were designed by DOT to examine issues of compatibility of different systems on tractors and trailers (Template 2) and to examine issues of performance and reliability of matched or optimized systems in which both tractor and trailer have advanced technology systems (Template 3). Table 1-1 shows that most objectives are common to both Template 2 and Template 3, with the exception of Objectives 6 and 7. Objective 6 focuses on compatibility of vehicles equipped with different control systems in Template 2, while Objective 7 focuses on the overall performance and safety benefits of ECBS and enabled safety technologies installed on married tractor-trailer pairs in Template 3.

Even if successful in their introduction into the marketplace, ECBS and other technologies tested in this program will not replace the legacy of current systems (ABS or non-ABS) immediately, but will enter the market at normal pace of replacement of tractors and trailers, which can span anywhere from 4 to 20 years. The new systems will be mixed with legacy technologies for many years to come and, therefore, must be fully compatible with existing technology. There will also be a potential for tractors equipped with ECBS from one vendor to be paired with trailers equipped with ECBS from a different vendor. As such, the objective of the Template 2: Mixed Tractor-Trailer test is to evaluate the compatibility and performance of tractors and/or trailers equipped with ECBS with tractors and/or trailers equipped with ABS or ECBS from different vendors. In addition to these electronic safety systems, the Freightliner Team has included evaluation of ADB in the Template 2 evaluation to capture critical information on the compatibility of ADB when mixed and matched with conventional drum brakes.

The objective of the Template 3: “Optimized” or Matched Tractor-Trailer test is to evaluate combination vehicles where both tractor and trailer are equipped with optimized and/or advanced ECBS technology. The systems under test incorporate one or more advanced brake system safety components to improve the vehicle’s crash avoidance capability. These systems include ACC, ESC (understeer, oversteer, yaw and roll stability), and roll stability technologies for tractors and trailers.

1.3 Freightliner Team

Freightliner assembled the following team to conduct an FOT of advanced brake systems and related safety technologies:

- **Freightliner LLC**, a leading truck manufacturer in North America, the Program Manager and Prime Contractor
- **Meritor WABCO** and **Bendix Commercial Vehicle Systems LLC (Bendix)**, the two leading suppliers of advanced braking systems and advanced vehicle stability control safety systems
- **Wal★Mart**, the largest retailer in the United States, distributing products nationwide with state-of-the-art fleet operations and maintenance tracking systems
- **Battelle**, the team integrator, experienced at organizing and facilitating FOTs as well as collecting, compiling, and transferring data
- **Aberdeen Test Center**, the field instrumentation provider, skilled at installing sensors and providing and maintaining data acquisition systems (DAS) on-board vehicles.

Other significant contributors to the program include:

- **General Electric TIP**, a unit of the General Electric Company, a leader in over-the-road trailer services and supplier of the GE VeriWise™ asset tracking for trailers
- **Great Dane Trailers**, the second largest trailer manufacturer in the world, recognized as an industry leader in technology, innovation, and quality
- **Hendrickson**, a leading supplier of air suspensions, axle systems, and metal bumpers for the heavy-duty transportation industry.

In addition to working with these important Freightliner Team stakeholders, the Freightliner Team worked closely and collaboratively with the **DOT** (the Federal Highway Administration, or **FHWA**; **FMCSA;** and the National Highway Traffic Safety Administration, or **NHTSA**) and its IE, **Booz Allen Hamilton**. In particular, the Freightliner Team worked in collaboration with DOT and its IE to develop a comprehensive, integrated approach for conducting the combined Template 2 and Template 3 FOT.

1.4 Freightliner Team Approach to Meet the Objectives

In Template 2, the Team fielded 40 tractors in four configurations and 60 trailers in four configurations to address Objectives 1 through 6, relating to performance, reliability, maintainability, durability, and compatibility of tractors and trailers from different vendors with advanced and conventional braking and safety systems. In the Template 3 test, the Team fielded eight tractors and 40 trailers with Meritor Wabco ECBS and advanced technologies to capture performance, reliability, and safety benefits data for Objectives 1 through 5 and 7. The two templates were conducted in parallel in a Wal★Mart fleet operating out of the Loveland, Colorado, distribution center. A total of 48 instrumented Freightliner Columbia tractors and 100 instrumented Great Dane trailers participated in the combined FOTs for 12 months.

Since many objectives and activities were common to both templates, conducting both templates in parallel provided benefits and cost efficiencies for the overall program in terms of planning, engineering design, data collection, equipment installation, equipment checkout, reporting, and briefings. Furthermore, joint conduct of Templates 2 and 3 by the Freightliner Team yielded a more comprehensive data set, with more opportunities for comparisons and safety benefits analyses than if the templates had been performed by different teams, with different technologies and different fleets.

1.4.1 Technical Approach

The Freightliner Team conducted the ECBS FOT program in two parts with five tasks as defined by the DOT:

Part 1: Program Planning, Vehicle Construction, and Instrumentation

- Task 1: Generate FOT Plan
- Task 2: Assemble Test Vehicle with ECBS
- Task 3: Conduct ECBS and DAS Check Out Testing

Part 2: Field Test and Data Collection

- Task 4: Conduct FOT
- Task 5: Project Reports and Deliverables.

The first part of the program focused on planning and working out the design and strategy for the program in collaboration with the DOT and IE in Task 1, as well as on preparation of the vehicles for the field test in Tasks 2 and 3. The Freightliner ECBS FOT Test Plan (Freightliner 2005), which provides a detailed outline of the tests and work to be conducted, was developed. The Freightliner Team combined Tasks 2 and 3, in which it built the tractors and trailers, integrated the safety systems on board, installed DAS, and conducted shakedown testing. The Team followed a structured build and check-out plan for ECBS, safety technologies, and DAS consisting of (1) Pilot Vehicle Design and Testing, (2) Check-Out Testing, (3) Shakedown Testing, and (4) Construction and instrumentation of the FOT Vehicles. Each step progressively built upon previous activities.

The second part of the program was the field test, including training of drivers and technicians, release of instrumented vehicles to Wal★Mart, data collection for 12 months, FOT logistics management, and the reporting phase of the program. The field test involved naturalistic, day-to-day product delivery operations of Wal★Mart operating out of its Loveland, Colorado, distribution center. All FOT vehicles were operated on similar road types, for similar average trip mileage and trip durations. The data collected included onboard driving data, i.e., data relevant to brake system performance and safety-related vehicle dynamics recorded continuously on the vehicles throughout the FOT; fleet operations and maintenance data; and surveys and interviews. Data collected onboard the vehicles were manually transferred at truck terminals by trained, designated individuals who removed and replaced the solid-state storage devices in the DAS. Following completion of the data collection, summary statistics generated during the FOT were compiled for this final report to the USDOT.

Further details of the program approach are provided in Section 3.0 of this report.

1.4.2 Program Schedule and Work Breakdown

The schedule for this program, which was initiated on May 1, 2003, is shown in Figure 1-1. Five primary tasks were described in the original solicitation.

- **Tasks 1 to 3**, conducted from May 1, 2003, through April 30, 2005, were dedicated to pre-FOT activities, focusing on FOT planning as well as vehicle, systems, and DAS design, implementation, and testing.
- **Task 4**, conducted for a period of 12 months from May 1, 2005, through April 30, 2006, was the FOT itself, under which the tractors and trailers were deployed in operating service and data were collected.
- **Task 5** consisted of the reporting activities for the program. The final reporting phase spanned approximately 5 months from May 1, 2006, through November 30, 2006.

The original schedule was revised in November 2004 to reflect delays encountered in material and parts supply for manufacturing, instrumentation of tractors and trailers, as well as readiness of the DAS data collection boxes.

WBS	Task Name	Start	Finish
1	**Task 1 - Generate Field Operational Test Plan with DOT Approval**	**5/1/03**	**8/31/04**
1.1	Review and Update FOT Strategy with Input from DOT, IE and FOT Team	5/1/03	12/31/03
1.2	Revise and Finalize FOT Test Plan	1/1/04	4/30/04
1.3	Request Internal Review Board (Human Subjects) Approval/Exemption	12/1/03	8/31/04
2	**Tasks 2 & 3 - Assemble Test Vehicles with ECBS and Conduct ECBS and DAS Check-out Testing**	**9/1/03**	**4/4/05**
2.1	Specify & Build Base Pilot Tractors and Trailers	9/1/03	2/27/04
2.2	Install and Test ECBS and Adv Technologies on Pilot Vehicles	3/1/04	5/31/04
2.3	Instrument Pilot Tractors and Trailers with Sensors and DAS	3/1/04	5/31/04
2.4	Conduct Track and Onroad Shakedown Testing of Pilot Vehicles	6/1/04	7/30/04
2.5	Revise Vehicle, Instrumentation and Validation Plans based upon Testing	6/1/04	7/30/04
2.6	Selection and Assignment of Drivers, Mechanics and Supervisors Finalized	7/15/04	7/15/04
2.7	Instrument Driver Profiling Tractors (existing)	7/15/04	9/1/04
2.8	Build FOT Tractors and Install ECBS and Advanced Technologies	9/1/04	12/31/04
2.9	Build FOT Trailers and Install ECBS and Advanced Technologies	9/1/04	2/1/05
2.10	Instrument FOT Tractors and Trailers with Sensors and DAS and Checkout	9/1/04	4/4/05
2.11	Build and Test Electronic Data Harvesting and Transfer System	5/3/04	4/4/05
2.12	Develop Plans and Procedures for Operations and Maintenance Data Collection and Transfer	5/3/04	4/4/05
2.13	Develop Plans, Materials and Procedures for Field Training and Support	5/3/04	4/4/05
4	**Task 4 - Conduct Field Operational Test**	**9/1/04**	**11/30/06**
4.1	Template 3 Phase 0 (PreFOT Driver Profiling) Data Collection	9/1/04	3/4/05
4.2	Conduct Field training - Drivers, mechanics and fleet management	2/1/05	4/1/05
4.3	Preparation of FOT Tractors and Trailers by Wal-Mart	2/2/05	4/4/05
4.4	Final Preparation and Validation of FOT Vehicles	2/2/05	4/4/05
4.5	Final Data Harvesting, Collection and Transfer Checkout	2/2/05	4/4/05
4.6	**Template 2 Onboard Data Collection and Assessment**	**5/1/05**	**4/30/06**
4.6.1	Template 2 Phase 1 - 6 mos - Technologies Turned Off	5/1/05	12/12/05
4.6.2	Template 2 Phase 2 - 6 mos - Technologies Turned On	12/14/05	4/30/06
4.7	**Template 3 Onboard Data Collection and Assessment**	**5/1/05**	**4/30/06**
4.7.1	Template 3 Phase 1 - 6 mos - Technologies Turned Off	5/1/05	12/12/05
4.7.2	Template 3 Phase 2 - 6 mos - Technologies Turned On	12/14/05	4/30/06
4.8	**Conduct Periodic Driver/Mechanic Surveys**	**3/7/05**	**8/15/06**
3.8.1	Baseline Surveys	3/7/05	3/21/05
3.8.2	Phase 1 surveys	3/1/06	3/15/06
3.8.3	Final Surveys	8/1/06	8/15/06
4.9	**Maintenance and Operations Data Collection and Assessment**	**5/1/05**	**9/30/06**
3.9.1	Phase 1 maintenance data	5/1/05	12/1/05
3.9.2	Phase 2 maintenance data	12/2/05	9/30/06
4.10	Transfer Data to IE	9/2/04	11/30/06
4.11	Decomissioning following Data Collection Phase	5/1/06	11/30/06
4.12	Freightliner Team Data Tabulation and Drafting Final Report	5/1/06	11/30/06
5	**Task 5 - Project Reports, Progress Reports and Deliverables**	**11/10/03**	**11/30/06**
5.3	**DOT Project Briefings**	**11/10/03**	**11/9/06**
5.6	Final report	11/30/06	11/30/06

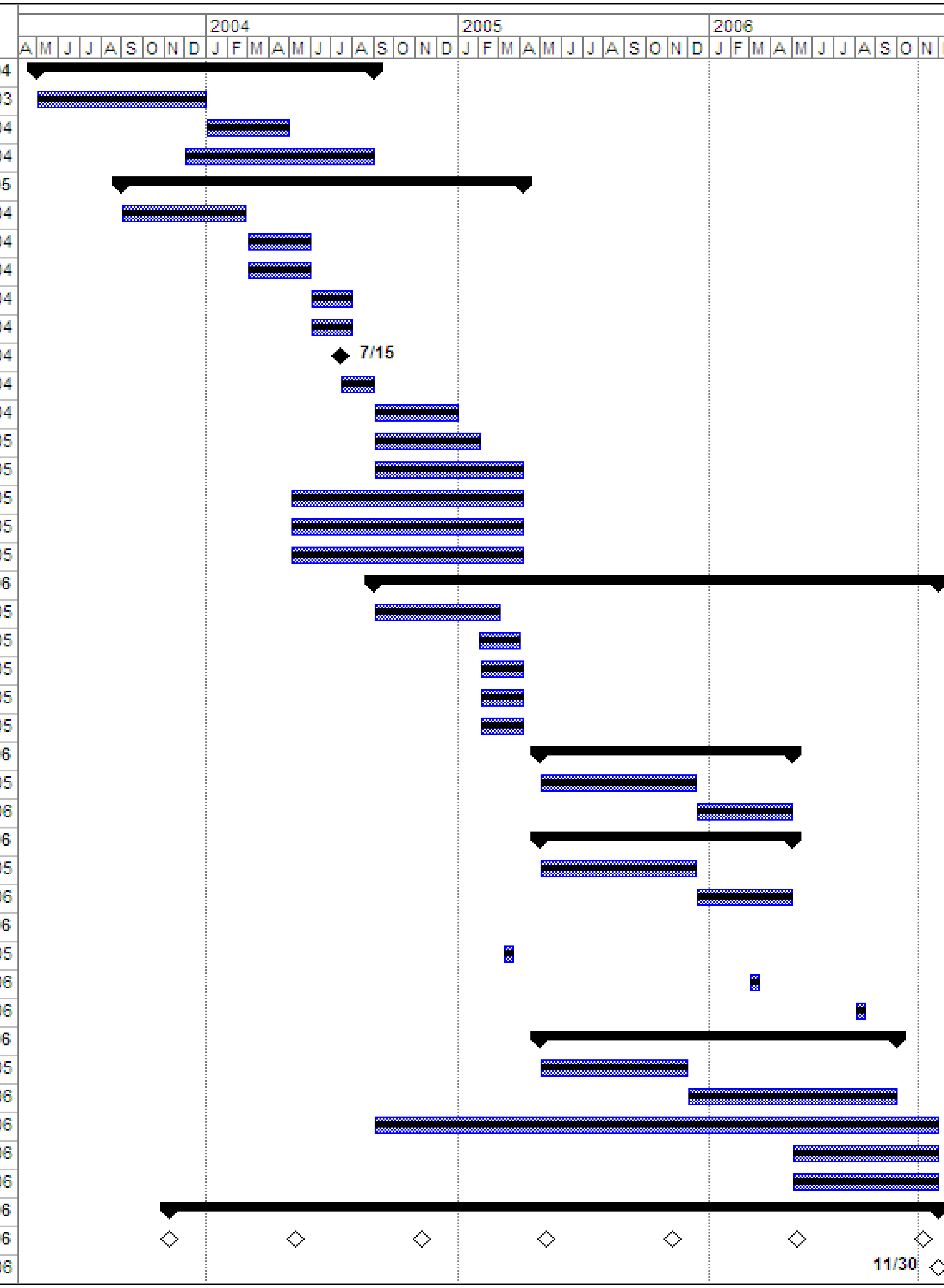


Figure 1-1. Field Operational Test Schedule

2.0 TECHNOLOGIES EVALUATED

The FOT was designed to support observation of technologies in operating service. In all cases, these newer technologies can be compared with conventional approaches to achieving the same end. The primary focus of the study was ECBS, which were compared with both standard and modern pneumatic brake control systems. A number of safety-enhancing technologies that are enabled by the advanced brake control systems were also evaluated. Finally, the foundation brakes themselves were being evaluated. For this, some trucks were equipped with S-cam drum brakes and some with ADB. This section provides a description of all the technologies under evaluation: foundation brake technologies, brake control technologies, and enabled safety technologies, as they were integrated onboard the FOT vehicles. The technologies installed on vehicles are listed per vehicle type (tractor or trailer) and configuration in Table 2-1. Several vehicles were equipped with identical technologies, hence defining groups or configurations. Additional details are provided in Section 3 and in appendices.

Table 2-1. Technologies Installed on Tractors and Trailers, Defining Vehicle Configurations

Vehicle Configuration & Type*		Foundation Brakes		Brake Control			Enabled				
		Drum	Disc	ABS	ECBS	ABS6	ACC	RSC	ESC	RSS	TRSP
T2C1	Tractors	●		●			●	●			
	Trailers			●							
T2C2	Tractors		●	●			●	●			
	Trailers		●	●							
T2C3	Tractors		●		●		●		●		
	Trailers		●		●					●	
T2C4	Tractors		●			●					
	Trailers		●		●						●
T3	Tractors		●		●		●		●		
	Trailers		●		●					●	

* Configurations of vehicles in Template 2 are referred to throughout this report by the corresponding Template number (T2) and group, or configuration, number (C1, C2, C3, C4). All vehicles in Template 3 are referred to by the Template number (T3) alone.

2.1 Foundation Brake Technologies

Drum brakes and disc brakes are the two most common mechanisms for generating brake forces in heavy vehicles. Both were in use in this study (Table 2-2). Drum brakes were not actually evaluated, but they were on trucks in control groups as a basis for comparison.

Table 2-2. Foundation Brakes Installed on FOT Tractors and Trailers

Template 2			Template 3		
Configuration	**Tractors**	**Trailers**	**Configuration**	**Tractors**	**Trailers**
Configuration 1	Drum Brakes	Drum Brakes	Profiling	Drum Brakes	Drum Brakes
Configuration 2	Disc Brakes	Disc Brakes	T3	Disc Brakes	Disc Brakes
Configuration 3	Disc Brakes	Disc Brakes			
Configuration 4	Disc Brakes	Disc Brakes			

Drum Brakes
Disc Brakes

2.1.1 S-cam Drum Brakes

Conventional S-cam drum brakes are found today on the majority of North American CMVs. These brakes were installed on the new tractors and trailers for Configuration 1 in Template 2 as a control group. This is also the standard type of brake used by Wal★Mart for its vehicles. Drum brakes were installed on the pre-existing Wal★Mart trucks (both tractor and trailer) for profiling the drivers in Template 3 (Phase 0).

S-cam drum brakes are mature products with a long history of effective service, and they are understood by all truck mechanics. However, they are subject to fade at high temperatures as the drum expands away from the shoes.

The drum brakes installed on tractors and trailers were manufactured by Meritor.

2.1.2 Air Disc Brakes

Most of the trucks and trailers in the study were fitted with ADBs. The ADBs were manufactured by Bendix-Knorr, model ADB22X, and by Arvin Meritor, model DiscPlus™ EX225 (Figure 2-1). The Arvin Meritor products were installed only on trailers in Template 2, Configuration 2 with spring suspension. The Bendix products were installed on tractors and on trailers also equipped with air suspension.

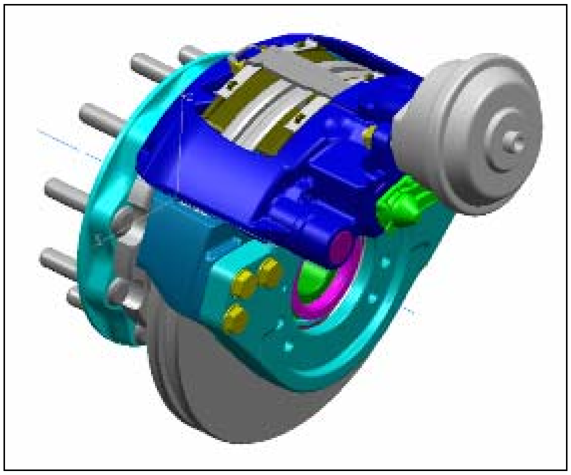


Figure 2-1. Bendix-Knorr, Model ADB22X (left) and Arvin Meritor DiscPlus™ EX225 (right) Air Disc Brakes

Disc brakes have certain advantages over drum brakes. Disc brakes are known to generate a linear brake torque output, to be consistent, stable, and resistant to fade. Indeed, in disc brakes, not only does thermal expansion bring the disc in closer contact with the pads, but also the exposed friction surfaces provide better thermal dissipation than is available with drum brakes. Maintenance costs of ADB are expected to be lower than for drum brakes because the components are more accessible. The primary disadvantage of disc brakes is that they require more force to generate the torque output than do drum brakes (because disc brakes have no self-energization, as do drum brakes). Also, the exposed friction surfaces are more sensitive to contamination and moisture than are drum brake surfaces.

Bendix product literature claims that the hysteresis of their ADB is under 10 percent. This improved consistency over drum brakes allows better steering control during stops. In Federal

Motor Vehicle Safety Standard (FMVSS) 121 tractor test stops from 60 mph, Bendix has measured the stopping distance to be 77 ft less for a typical 56,470-lbs gross vehicle weight tractor equipped with ADB and coupled to a control trailer (non-braked) than a comparable vehicle with drum brakes. The same size brake unit can be mounted on all axles of a truck and/or trailer, and borrowing wheel hubs of sufficient size are used.

2.2 Brake Control Technologies

Three kinds of brake control technologies were used in this study. One group of vehicles had conventional ABS, which are the minimum required on new heavy vehicles in the United States. Another group was equipped with ECBS. A third group of tractors had ABS6, which is the next generation of Bendix ABS. Table 2-3 below summarizes the brake control system that was installed on each vehicle in the FOT.

Table 2-3. Brake Control Technologies Installed on FOT Tractors and Trailers

Template 2			Template 3		
Configuration	Tractors	Trailers	Configuration	Tractors	Trailers
Configuration 1	ABS	ABS	Profiling	ABS	ABS
Configuration 2	ABS	ABS	T3	ECBS	ECBS
Configuration 3	ECBS	ECBS			
Configuration 4	ABS6	ECBS			

2.2.1 ABS

Air brake systems are required by FMVSS 121 to have ABS capability. ABS was the standard brake control technology on some of the trucks in this study and on Wal★Mart standard fleet tractors and trailers. The basic function of ABS is to prevent wheel lock during severe braking by monitoring wheel speed and modulating air pressure in the brake chambers. Tires can provide higher lateral forces (and hence better stability) when they are rotating than when they are locked and sliding on the road surface.

The benefits of ABS include:

- Enhanced steerability under emergency braking
- Enhanced stable stopping on icy or wet roads, and in curves
- Reduced stopping distance
- Reduced potential for tractor-trailer jackknifing
- Reduced potential for tire damage.

The ABS was manufactured by WABCO, and had 6S/4M and 4S/2M functionality[3] on tractors and trailers, respectively.

2.2.2 ECBS

The basic function of ECBS is similar to that of ABS, i.e., ECBS prevents wheels from locking during high-demand stops on reduced-friction surfaces. However, ECBS controls actuation of the foundation brakes with electronic signals rather than pneumatic control lines. The energy that actually applies the brakes is pneumatic (air pressure), so the brakes are still air brakes; in ECBS only the control is electronic. In fact, ECBS requires no change to the foundation brake itself. The friction material (drum or disc), slack adjuster (on drum brakes), and brake chamber are identical to those on trucks with pneumatically controlled brakes. Pneumatic control lines are still present to serve as a backup control system in case of failure of the electronic control.

Replacing the pneumatic logic of controlling and proportioning the brakes with electronic hardware and software enables integration of the brakes with the other electronics on the vehicle, making possible many of the “enabled technologies” described below. ECBS shortens the response time required for the brake pressure to build up on all axles. It improves brake force

[3] Modern ABS all feature the following major components: Electronic Control Unit (ECU), modulator valves, wheel speed sensors, and ABS malfunction indicator lamp(s). ABS configuration is defined by the arrangement and number of sensors and modulator valves used. The most common configurations for tractors are: four sensors/four modulators (4S/4M), six sensors/four modulators (6S/4M), and six sensors/six modulators (6S/6M). Common configurations for trailers are 2S/1M, 2S/2M, 4S/2M, and 4S/3M.

distribution and equalizes lining wear. The logic allows optimization of road adhesion and better proportions the braking demands between the tractor and the trailer. All of these effects provide better stability and shortened stopping distances.

ECBS also improves the driver's ability to control vehicle deceleration. In conventional pneumatically controlled braking, the brake treadle force applied upon driver demand determines the control pressure. By compensating for brake hysteresis, ECBS replaces driver-selected pressure control with driver-selected deceleration control. ECBS does change the feel of the pedal when fade is present. When connecting a tractor with ECBS to a trailer with ECBS, the driver must join an extra seven-pin connector. Aside from that, the driver does not need to take any special actions to use ECBS.

Electronic control allows improvements in the operation of the brakes and braking system, which can enhance safety and reduce driver workload. For example, with a conventional braking system, the driver must apply more brake pressure to stop a heavier load than required for a lighter load. In contrast, ECBS controls vehicle deceleration, such that, for a given brake pedal position, ECBS vehicles will decelerate at a fixed rate, regardless of the load on the tractor and trailer. This potentially reduces the stress on the driver and the need for constant adjustment for truck load and brake condition. At the same time, ECBS can improve the vehicle stability and braking performance through wheel-by-wheel adjustment of braking in response to changing conditions including load shift, road friction, and hysteresis. The capability of ECBS systems to diagnose themselves can also reduce maintenance costs.

While these benefits are valuable on their own, electronic controls provide substantial additional benefit by serving as an enabling platform for other advanced safety systems that have the potential to reduce the likelihood of rollover, jackknife, or loss of control from understeer and oversteer in a curve. ECBS also enables the use of an integrated ACC system that controls vehicle speed and following distance with foundation brakes, as well as throttle control and engine brake, which again has the potential to reduce driver workload.

Manufacturers such as Meritor WABCO and Bendix provide a software diagnostics tool to read faults codes and their descriptions, to test components, and to display system data. With these diagnostic tools, ECBS helps mechanics by continuously monitoring the brake system for performance, wear, and air leaks. The diagnostic tool can also interrogate the pressures, voltages, the gap of the wheel speed sensors, and diagnostic codes.

The ECBS installed on the tractors in this FOT had 4S/4M ABS capability and were manufactured by Meritor WABCO. The Meritor WABCO ECBS also included automatic traction control (ATC), generally described below under Enabled Technologies. The ECBS installed on the trailers had 4S/2M ABS capability and were manufactured by Meritor WABCO and Bendix.

Indicator lamps were installed in the tractor dashboard to inform drivers in the event of a fault with the system and to notify drivers if a particular technology was active (Figure 2-2).

All tractors equipped with ECBS in the FOT were equipped with the Meritor WABCO ECBS. The trailers in Template 2 Configuration 3 and Template 3 were equipped with Meritor WABCO ECBS. The trailers in Template 2 Configuration 4 were the only vehicles in the FOT equipped with the Bendix ECBS product, TEBS4 (TEBS = Trailer Electronic Braking System), or Trailer ECBS Module Gen 4. When installed on trailers, the ECBS provided a single electronic brake control with a single pneumatic backup circuit. However, when the trailers equipped with the Meritor WABCO ECBS were paired with a tractor having Meritor WABCO ECBS, the vehicle had full ECBS functionality. As noted above, a second trailer connector was required to provide this added functionality.

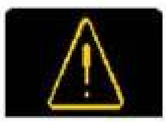
When the indicator(s)…	… is/are lit:
	Indicates faults with ECBS
	Indicates faults with ABS If equipped with appropriate enabled technologies : Indicates ATC, ESC or LWC faults
 	Pneumatic backup mode
	If equipped with appropriate enabled technologies : Indicates ATC or ESC is active
When the indicator…	**… is blinking:**
	If equipped with appropriate enabled technologies : Indicates ATC deep snow and mud mode is active

Figure 2-2. Indicator Lamps for Drivers on Tractors Equipped with Meritor WABCO ECBS

Figure note: ECBS – Electronically controlled braking system;
ABS – Antilock braking system; ATC – Automatic traction control;
ESC – Electronic stability control; LWC – Lining wear control.

2.2.3 ABS6

ABS6 is the next generation of ABS technology for tractors offered by Bendix. ABS6 actuates brakes through pneumatic control signals like conventional ABS, but it can also provide enhanced capabilities not found in conventional ABS.

The ABS6 is available commercially in three configurations: standard, premium, and advanced. The premium level, which was evaluated in this FOT, was installed on the Template 2 Configuration 4 tractors. It allowed greater diagnostic and prognostic capabilities than earlier Bendix products. The Premium level ABS6 included conventional ABS capability (in this FOT, 6S/4M), and ATC, generically described below under Enabled Technologies. Premium ABS6 had the authority to adjust the engine torque when necessary. All commercial versions have architecture, including sensors and relays that are similar to those in conventional ABS.

Special features of the Bendix Premium ABS6 include the ability to blend the brake force between the two wheels on the steer axle to reduce the side pull when the friction under the two wheels is significantly different. When the vehicle is in thick mud or other special conditions, the driver can select an “off road” ABS mode, which allows the wheels to lock during braking.

2.3 Enabled Technologies

Modern braking systems can perform functions beyond merely stopping the vehicle. For example, they can help the driver maintain control of the vehicle in adverse driving conditions. They can also adjust the brake pressure according to the conditions of the individual brake linings. Many of the capabilities enabled by recent developments were evaluated in this FOT.

Some of these enabled technologies (i.e., ACC, RSC, and ESC) are designed only for the tractor. Two technologies that assist with roll stability are designed for trailers: RSS and the Trailer Roll Stability Program (TRSP) ™ (Bendix). Two distinct systems for monitoring the physical conditions of the brakes—brake performance monitoring (BPM) and lining wear sensing and control (LWS&C)—were deployed on various vehicles in the FOT. In addition, some tractors were equipped with ATC, because the technology was bundled with other enabled technologies. ATC per se was not evaluated in this FOT.

Training materials for the safety-related systems caution the driver that no technological device can prevent all accidents of a certain type and that the driver must remain fully in charge of the vehicle’s safety.

Table 2-4 below summarizes which cruise control technology, if any, was installed on the vehicles as a function of template and configuration.

Table 2-4. Configurations for Examining Cruise Control Technology

Template 2			Template 3		
Configuration	**Tractors**	**Trailers**	**Configuration**	**Tractors**	**Trailers**
Configuration 1	ACC	-	Profiling	-	-
Configuration 2	ACC	-	T3	ACC	-
Configuration 3	ACC	-			
Configuration 4	CCC	-			

ACC – Adaptive cruise control
CCC – Conventional cruise control

2.3.1 Adaptive Cruise Control

Adaptive cruise control (ACC) helps the driver maintain a safe following distance behind the vehicle ahead of the truck or maintain a pre-set constant speed (Figure 2-3). It uses a radar (Figure 2-4) to sense other vehicles ahead and, when necessary, slows the truck.

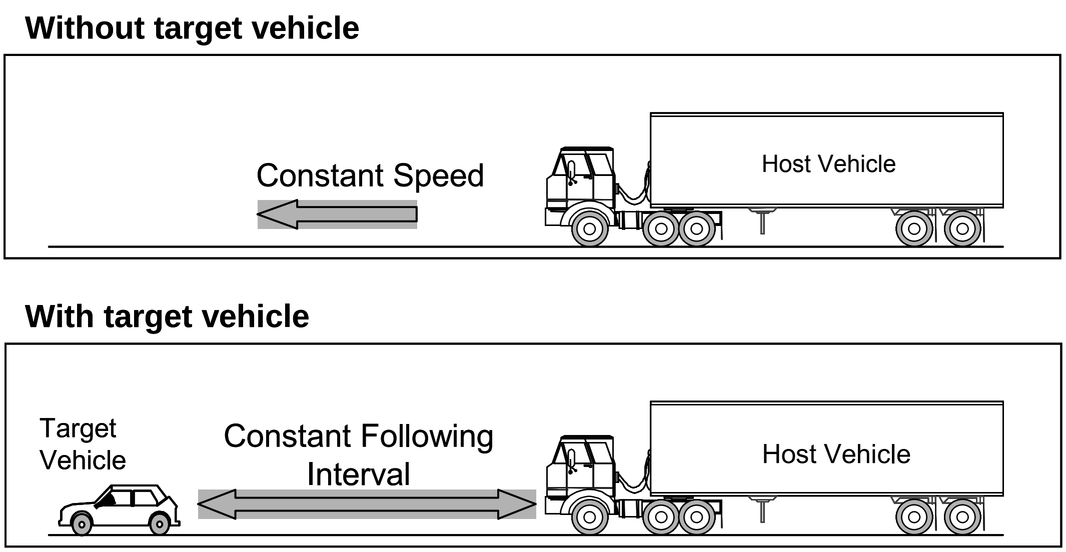


Figure 2-3. Principle of Operation of Adaptive Cruise Control

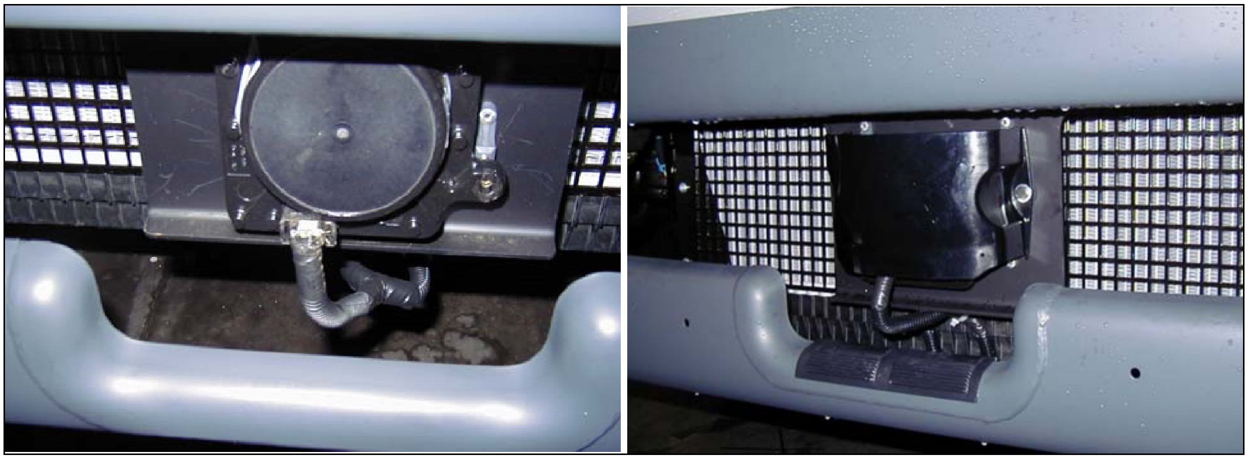


Figure 2-4. Radar Antenna Mounted Near the Front Bumper without (left) and with Cover (right)

The driver operates the system in a manner similar to conventional cruise control (CCC). Rather than selecting a constant speed for the truck to automatically maintain, with ACC, the driver is actually selecting a maximum speed, which the truck will maintain when there is no lead vehicle in the lane on front of the truck. A display screen to the right of the steering wheel (shown in Figure 2-5) keeps the driver apprised of the system's status. It tells the driver when the system is active and what the maximum set speed is. If a lead vehicle is detected, the system tells the driver of the other vehicle's presence, its speed, and the gap between the two vehicles. If the truck is closing on the lead vehicle, the system will reduce the vehicle speed to match that of the lead vehicle and maintain the following distance. To do so, the system will first decrease engine torque, apply a retarder, downshift the transmission (if it is automatic), and apply the foundation brakes (up to 0.25g) as it deems necessary. If the vehicle is closing rapidly, the system will alert the driver through audible and visual signals. When there is a fault, the display also informs the driver, and the system shuts down.

Figure 2-5. ACC Display Installed in the Tractor Dash

Tractors equipped with ACC also have a collision warning system (CWS). The CWS sounds an alarm and displays a warning indicator (Figure 2-6) if the system detects another vehicle too close in front of the tractor. CWS is merely a warning system; it does not slow the truck. The collision warning function is always operating, regardless of whether the cruise control is activated.

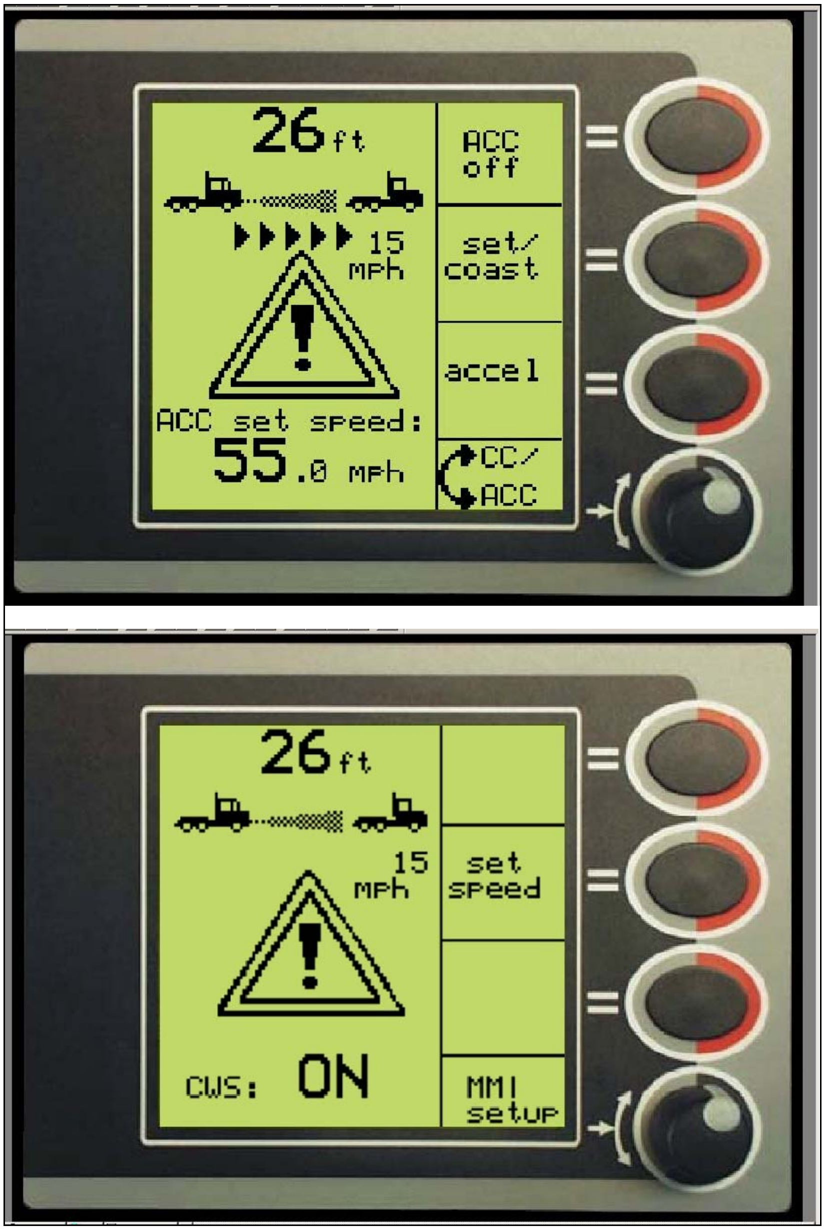


Figure 2-6. Warning Indicator Displayed by the Collision Warning System when ACC is On (top) and Off (bottom)

The key to the ACC system is a radar with a detection range of approximately 20 to 450 ft. It operates at 76 to 77 GHz. An Electronic Control Unit (ECU) gathers the information collected by the radar and, if the data are indicative of the presence of the lead vehicle within the detection range, the system ECU calculates the distance to the lead vehicle and the relative speed of the two vehicles. The radar can measure the azimuth (direction) of target vehicles. It combines that information with the road curvature, which is estimated from the tractor's measured yaw rate, to determine whether a target is in the same lane as the truck. The ECU communicates with the rest of the vehicle through the Society of Automotive Engineers (SAE) J1939 bus[4], which is now virtually universal on high-end commercial vehicles.

ACC was manufactured by Meritor WABCO and installed on all tractors equipped with WABCO ABS or Meritor WABCO ECBS. While the way foundation brakes are applied differs between the vehicle platforms, the functionality of ACC is the same on tractors equipped with ECBS and ABS. On a tractor equipped with ABS, ACC applies the brakes by activating the solenoid valve for the ATC. On a tractor equipped with ECBS, ACC applies the brake by sending an electronic control signal using the ECBS network. As such, ACC can more directly and readily control the foundation brake applications when the vehicle is also equipped with ECBS.

Several technologies installed on the FOT tractors and trailers were designed to enhance vehicle stability, i.e., reduce the risk of stability-based incidents such as rollovers and jackknifes. Table 2-5 below summarizes which enabled stability-based technology, if any, was installed on the vehicles as a function of template and configuration.

Table 2-5. Configurations for Examining Stability-Based Technology

Template 2			Template 3		
Configuration	**Tractors**	**Trailers**	**Configuration**	**Tractors**	**Trailers**
Configuration 1	RSC	-	Profiling	-	-
Configuration 2	RSC	-	T3	ESC	RSS
Configuration 3	ESC	RSS			
Configuration 4	-	TRSP			

RSC – Roll stability control
ESC – Electronic stability control
RSS – Roll stability support
TRSP – Trailer Roll Stability Program™

[4] SAE J1939 is a series of SAE Recommended Practices that define architecture and protocol for a serial control and communications network (i.e., a data bus) for various equipment types. Similarly, SAE J1587 is a joint SAE/Truck Maintenance Council (TMC) Recommended practice for electronic data interchange between microcomputer systems in heavy-duty vehicle applications.

2.3.2 Roll Stability Control

Roll stability control (RSC) was one of several systems in the FOT that could apply one or more brakes to help improve the stability of the vehicle and avoid various kinds of single-vehicle crashes. RSC is a Meritor WABCO product that operates on tractors with conventional ABS. The RSC continuously monitors a tilt sensor (an accelerometer) contained in the ECU, which is normally mounted on the vehicle frame. When the RSC senses that the vehicle is in danger of rolling over, most likely from rounding a curved exit ramp too fast, it slows the truck. The RSC automatically engages when needed; the driver does not have to take any action.

When the RSC activates, it always first de-throttles the engine, and then may apply the retarder, and engage the foundation brakes on the tractor's drive axles and on the trailer. As with Meritor WABCO's ACC on conventional ABS tractors, the brakes are applied by activating the solenoid valve for the ATC.

RSC partly senses and estimates the roll threshold of the vehicle by estimating the mass of the combination vehicle and inferring the height of the trailer's center of gravity. The ECU communicates with the tractor through the J1939 bus.

The driver is notified of the presence of the RSC when the tractor is turned on, and it momentarily lights the ATC lamp while it is engaged. A continuously lit ATC lamp indicates to the driver that the ATC or RSC has a fault (Figure 2-2).

2.3.3 Electronic Stability Control

Electronic stability control (ESC), like RSC, can apply the brakes to slow the truck and reduce the possibility of rollover. In addition, it can apply tractor brakes individually to support steering stability and prevent yaw-induced instabilities. ESC is a Meritor WABCO product that was installed on the tractors in the FOT equipped with Meritor WABCO ECBS.

As with the other stability-enhancing systems (RSC, RSS, TRSP), the driver does not operate the ESC. The ESC activates in an appropriate manner when necessary and informs the driver, through an indicator lamp, that it is doing so. Of course, the driver may also sense the slowing of the vehicle, or the reduced engine torque, retarder, or service brakes. The software tools provided to the mechanics for diagnosing faults with the ECBS include features for troubleshooting the ESC when necessary.

The functionality of the roll stability feature of the ESC is essentially identical to the ABS-based RSC. When working to prevent a roll, the ESC will always reduce the torque of the engine. If the magnitude of the rollover risk is greater, it will engage the retarder or apply the service brakes on the steer, drive, and trailer axles. The ESC, like the RSC, can help prevent so-called "untripped" rollovers—those that occur on the road when friction is good. (Tripped rollovers are those that occur when, for example, a truck strikes a curb or rolls down an embankment.)

When friction is poor, the greater concern is yaw control, or the driver's ability to steer. The truck may jackknife or plow out ("oversteer" or "understeer," respectively). The ESC, unlike the other stability systems in the FOT, can address steering (yaw) stability as well. It selectively applies one of the steer axle brakes to keep the tractor aligned with the roadway, while applying brakes on both sides of the drive axle to slow the vehicle. The ESC continuously monitors the driver's intended path by measuring the steering wheel angle. ESC determines whether the tractor is turning according to the driver's intentions. If the actual turning matches the intended path curvature, all is well. If the tractor starts to turn more sharply than the driver intended, a jackknife is about to occur, so the ESC will brake the steer tire on the outside of the curve, to correct the tractor's angle and ensure that the tractor turns as the driver intended. If the tractor is turning less sharply than the driver's steering wheel angle is requesting, ESC will brake the drive tire on the inner side of the curve (Figure 2-7).

Meritor WABCO's ESC functions as an extension of the ECBS. It requires two extra components beyond those for the ECBS: an ESC module, which includes a yaw rate sensor and a lateral accelerometer, and a steering angle sensor for the steering wheel. ESC also needs to know the vehicle's speed, which is measured by the tone rings for ABS. The ESC module is mounted to the frame of the tractor so its sensors can properly measure the motion of the tractor.

The built-in microprocessor continuously monitors the likelihood of both rollover and loss of control, and will quickly apply the appropriate braking when needed.

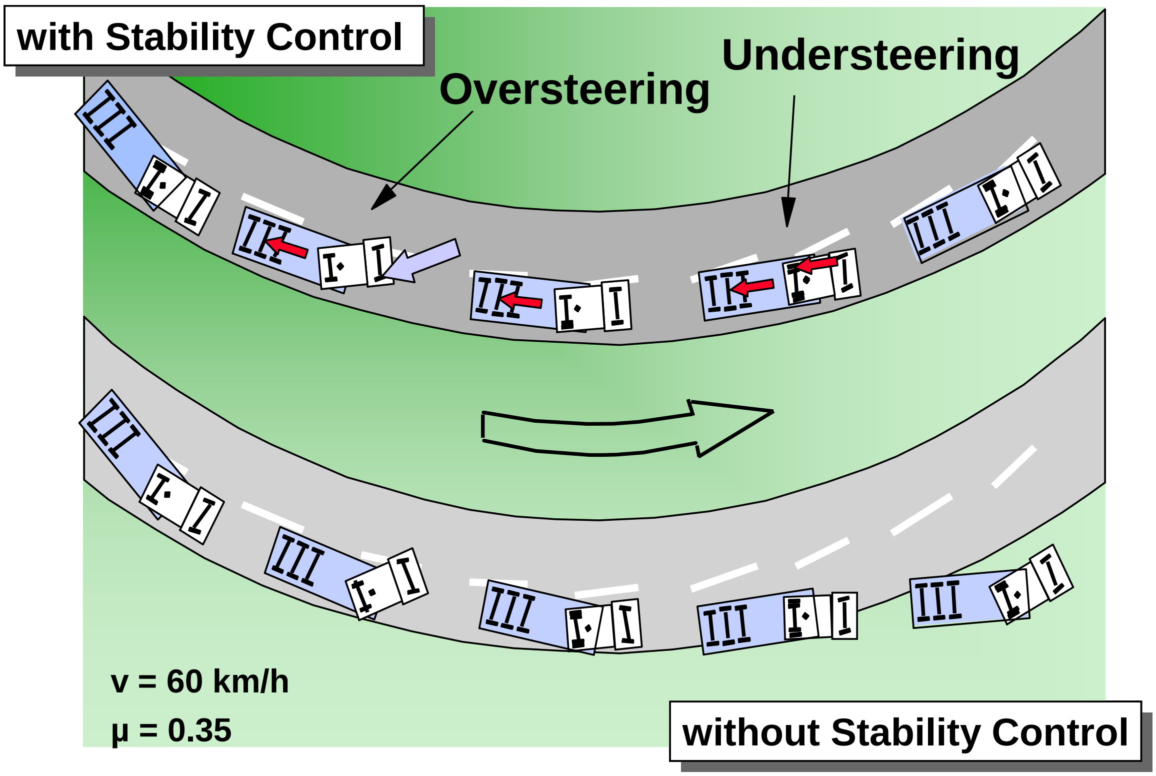


Figure 2-7. ESC Control Strategies in Yaw-induced Instabilities

The driver is notified of the presence of the ESC when the tractor is turned on, and when it is active as it momentarily lights up the ATC/ESC lamp (Figure 2-2). When a fault occurs in the ESC, the driver is notified by the ABS lamp, and the ESC shuts down. ESC diagnostics are included in the ECBS computerized diagnostics tool.

2.3.4 Roll Stability Support

Meritor WABCO's roll stability support (RSS) is a trailer technology enabled by Meritor WABCO trailer ECBS. RSS slows the trailer, hence the truck, when the driver is rounding a curve too fast and is in danger of rolling over. In its purpose, RSS is similar to RSC, but RSS operates independently of the tractor's brakes. The driver does not need to operate RSS; like the other stability systems evaluated in the FOT, it activates itself when necessary. RSS communicates with the driver through the trailer ABS lamp mounted in the dash.

RSS, like the RSC, must infer the roll threshold of the vehicle. While RSC uses a combination of engine torque and acceleration, RSS bases its estimate of the trailer's mass on the air pressure in the air suspension system. When the RSS detects a high lateral acceleration, it will briefly and gently apply the trailer brakes to test the actual rollover propensity. If an imminent rollover is confirmed, RSS will apply the brakes on the outer side at full pressure and the brakes on the inner side at a lower pressure. The driver's braking inputs have priority: if the driver commands a braking level greater than RSS is providing, RSS will switch off.

RSS is integrated with the ECBS system on the trailer. It requires no specialty hardware, though the control line must have a filter, and brake lights must be LEDs. RSS operates independently of the tractor's braking system, which can be ABS or ECBS, with or without a stability-enhancing system of its own. The ECU has a connection to a computer to help mechanics diagnose problems.

2.3.5 Trailer Roll Stability Program™

The Bendix Trailer Roll Stability Program™ (TRSP) is a trailer-based technology enabled by the Bendix ECBS. This technology was deployed on the Template 2 Configuration 4 trailers. TRSP, like the Meritor WABCO RSS, intends to reduce the likelihood of rollovers using a system completely contained on the trailer. The system includes a lateral accelerometer to measure the side forces developed while a trailer rounds a curve.

In a manner conceptually similar to the RSS, the TRSP first gently applies the brakes to all trailer tires when it detects a lateral acceleration that is high enough to cause concern. If the trailer truly is in danger of rolling over, the wheels on the inside of the curve will be lightly loaded (i.e., the centrifugal force of the turn will be lifting those wheels upward away from the ground), and the ABS wheel spin sensor will note that they are slowed considerably by the gentle braking. The TRSP will then apply the trailer brakes strongly to slow the truck and reduce the chance of rollover. The sudden slowing will alert the driver to the situation. Should the trailer be firmly on the ground when the gentle, test application occurs, the rotation of those inside wheels will be unchanged, and the system will learn that the trailer is loaded in a relatively stable configuration.

2.3.6 Brake Performance Monitoring

A brake performance monitoring (BPM) system was deployed on the Meritor WABCO ABS tractors (Template 2, Tractor Configurations 1 and 2). The monitoring process is based on ABS wheel speed signals. Two mileage counters are used: one to measure the unbraked distance traveled, and the other to measure the braked distance traveled. The system is designed to compensate for the different tracks of wheels when negotiating a curve, by comparing the wheel speed values of wheels that are diagonal to each other.

The BPM system stores and transmits messages as with other ABS data elements, and stored information can be extracted using diagnostic software. The goal is for the BPM system to detect a 30 percent reduction in brake performance, based on comparisons of slip among different wheels.

2.3.7 Lining Wear Control

Lining wear control (LWC) technology is intended to detect uneven brake lining wear and balance the wear across all brakes. In a non-critical braking process, the brake force distribution is adjusted according to the wear signals received by the LWC technology from lining wear sensors, if a variance in lining wear is perceived. The pressure on the wheel brakes showing more wear is reduced slightly, the pressure on the wheel brakes showing less wear being increased correspondingly, thus ensuring that the total retardation requested by the driver is provided. Individual control according to the wear criteria on both front and rear axles harmonizes lining wear. By evenly spreading the load across all wheel brakes, total wear is minimized. In addition, maintenance and lining change intervals coincide.

LWC was installed only on Meritor WABCO ECBS tractors in this FOT.

2.3.8 Lining Wear Sensing

Lining wear sensors (potentiometers for disc brakes or limit switches for drum brakes) were installed at each individual wheel to monitor the degree of wear of the linings in the wheel brakes on FOT trucks. LWS was installed by Bendix on their ADB on tractors equipped with Meritor WABCO ECBS and LWC. The sensor signals from the tractor front axle are picked up by the central module; those from the rear axle by the axle modulator. Signal processing and error monitoring for the rear axle are covered by the axle modulator, permitting the sensor values to be made available to the central module via the data bus.

2.3.9 Automatic Traction Control

Automatic traction control (ATC, also known as “traction control,” traction control system, or TCS) is a commercial product already installed on 10 percent of the large trucks in North America. ATC prevents the drive tires from spinning excessively when road friction is low, as in mud or snow. When the wheel speed sensor detects that a wheel has begun to spin too quickly, a solenoid valve opens to apply the brake and slow the wheel. A light in the cab alerts the driver that the ATC is activated (Figure 2-2). Drivers can activate or de-activate the system for deep snow or mud conditions. ATC was installed on all tractors equipped with ECBS or ABS6 in this FOT.

3.0 FIELD OPERATIONAL TEST

Task 1 of the project was dedicated to the development of the Field Operational Test Plan. The Freightliner Team developed an approach in its proposal (Freightliner 2003) without knowledge of the IE's approach to evaluating the technologies (Booz Allen Hamilton 2004). As such, the initial task of the project was specifically designed for the USDOT, the Freightliner Team, and the IE to work together to further refine the Freightliner Team's approach and to ensure that all objectives of the USDOT would be met. This section highlights the activities that took place in Task 1, and then describes the elements of the Field Operational Test Plan (Freightliner 2005).

3.1 Task 1: FOT Test Plan

3.1.1 Chronological Description of Work Performed

Following the announcement by the USDOT of the selection of the Freightliner Team as conductor Team for the ECBS FOT on May 1, 2003, the project kickoff meeting was held on June 10, 2003, with representatives of the USDOT, the IE, and the Freightliner Team. The Freightliner Team presented its approach as defined by its combined template technical proposal (Freightliner 2003) and learned about the evaluation approach of the IE (Booz Allen Hamilton 2004). During this initial period of the program, members of the Freightliner Team worked together to review and, if necessary, revise strategies and plans for the FOT. These meetings included regular conference calls and visits with the fleet, vehicle manufacturers, technology vendors, and data instrumentation partners. Strategies and plans including system design, technology integration plans, and implementation for data collection were reviewed in depth and revised as needed.

Following the initial kickoff meeting, the USDOT, the IE, and the Freightliner Team held a workshop at the USDOT on August 6, 2003, to further review the technical approach proposed by the Freightliner Team. Also, changes resulting from information received from team members, and from the needs of the evaluation approach presented by the IE, were discussed. After appropriate adjustments to the technical approach were identified, worked out, and integrated within the test plan, the Freightliner Team convened all teams in a workshop at Freightliner's headquarters in Portland, Oregon, on December 9, 2003. Representatives of the USDOT, the IE, and the Freightliner Team at large participated, including Freightliner, Battelle, Meritor WABCO, Bendix, the Aberdeen Test Center, and Hendrickson. During the workshop, consensus was obtained on the path to move forward, integrating the Conductor Team's proposed plan with the IE evaluation plan, to create an FOT plan. The draft FOT test plan was submitted to the USDOT for review (Freightliner 2004a), then finalized and submitted to the USDOT after incorporation of the USDOT's comments (Freightliner 2005). The final FOT test plan reflected all changes and adjustments to the original technical proposal submitted to the USDOT (Freightliner 2003).

3.1.2 Elements of the FOT Test Plan

This section describes the elements of the FOT test plan: experimental design (vehicle specification, quantities of vehicles, data collection schedule) for both Templates 2 and 3, Wal★Mart fleet operation specifics, and data collection/management information. First, this section highlights elements of the experimental design which, by impacting the data collected in the FOT, are instrumental to the evaluation of the technologies and analyses conducted by the IE. Then, details on the Wal★Mart fleet operations are presented: the service area and routes driven by the tractors, the vehicle tracking practices, the maintenance management, and the drivers are described. Finally, relevant elements of the data collection and management plan are presented.

3.1.2.1 Experimental Design

This section provides an overview of the FOT experimental design elements first for Template 2 and then for Template 3. Specific elements discussed are vehicle specifications, vehicle quantities, vehicle on-board DAS, and the data collection schedule (test phases). Additional details can be found in the final Test Plan (Freightliner 2005). The Freightliner Team carefully developed the experimental designs of both Template 2 and Template 3 to ensure that data were collected appropriately and in quantities sufficient to yield objective and statistically significant results.

Template 2: Mixed Tractor-Trailer Combinations

In Template 2, tractors and trailers with various brake technologies were mixed and matched to evaluate compatibility and performance of the technologies.

Quantities and Specifications of Tractors and Trailers

The original solicitation required that a minimum of 10 tractors equipped with ECBS from one supplier and 10 trailers equipped with ECBS from a different supplier be placed in an operating environment, allowing ECBS vehicles to be paired with each other and with non-ECBS equipment. In addition, the original solicitation encouraged the inclusion of "Advanced Brake Safety System Components," i.e., advanced safety technologies.

The Freightliner Team proposed to evaluate ECBS from Meritor WABCO and Bendix, as well as novel brake technologies, specifically disc brakes and a new-generation ABS for tractors, the Bendix ABS6. Tractors and trailers were placed into four (4) groups based on their brake configurations (combination of the type of brake control and the type of foundation brake), as shown below:

Configuration 1. ABS and drum brakes (tractor and trailer)
Configuration 2. ABS and disc brakes (tractor and trailer)
Configuration 3. ECBS and disc brakes (tractor and trailer)
Configuration 4. ABS6 and disc brakes (tractor), ECBS and disc brakes (trailer only).

The first group of tractors and trailers, Configuration 1, was representative of vehicles used by most fleets today, Wal★Mart included. The second group, Configuration 2, was similar to Configuration 1 except that the vehicles were equipped with disc brakes rather than drum brakes. Configuration 3 vehicles had the same foundation brakes as Configuration 2 vehicles (disc), but the brake control was ECBS rather than ABS. Finally, Configuration 4 tractors were equipped with a new-generation ABS, the Bendix ABS6, and trailers were equipped with a Bendix-provided ECBS. In essence, Configurations 3 and 4 vehicles represented the new generation of vehicle braking systems offered by Meritor WABCO and Bendix at the time of the design of the FOT, respectively. These are sometimes referred to as "next generation" systems.

Since these tractors and trailers were paired randomly in operations, the various configurations of tractors and trailers yielded a total of sixteen (16) possible mixed or matched combinations, and associated relevant ECBS/ABS compatibility and performance data, as illustrated in Table 3-1. Data from various mixed vehicle combinations were available for analyses: ABS tractors paired with ECBS trailers, ECBS tractors paired with ABS trailers, and ECBS tractors paired with ECBS trailers from a different vendor.

Table 3-1. Matrix Table Showing all 16 Possible Combinations of Tractors and Trailers (Template 2), with Corresponding Combination Type: Matched (✓) or Mixed (×)

Tractor \ Trailer	C1 MW ABS drum brakes	C2 MW ABS disc brakes	C3 MW ECBS disc brakes	C4 BDX ECBS disc brakes
C1 MW ABS drum brakes	✓	×	×	×
C2 MW ABS disc brakes	×	✓	×	×
C3 MW ECBS disc brakes	×	×	✓	×
C4 BDX ABS6 disc brakes	×	×	×	×

C# Configuration # MW Meritor WABCO BDX Bendix

In addition to the brake systems under evaluation as listed above and in accordance with the recommendations of the original solicitation, all tractor-trailers were also equipped with safety technologies enabled or enhanced by ECBS or ABS:

- ECBS-enabled technologies
  - ACC
  - ESC
  - RSS or TRSP™
  - Lining wear sensing and control (LWS&C)
- ABS-enabled technologies
  - ACC
  - RSC
  - BPM

Figures 3-1 through 3-8 illustrate the brake-related technologies that were evaluated on each tractor and trailer configuration in Template 2.

A summary of the vehicle specifications combining foundation brakes, brake control systems, and enabled technologies is included in Table 3-2 for the four configurations of tractors and trailers. Corresponding quantities of vehicles are also shown in the table. A total of forty (40) tractors and sixty (60) trailers were equipped with ECBS or ABS technology, instrumented, and evaluated in this template. The ratio of FOT trailers to FOT tractors was increased to 1.5 to facilitate the matching of the Template 2 tractors with Template 2 trailers. Because of the nature of Wal★Mart operations, the tractors and trailers were assigned randomly to each other within a sub-fleet. Increasing the number of trailers increased the probability of matching vehicles within the sub-fleet.

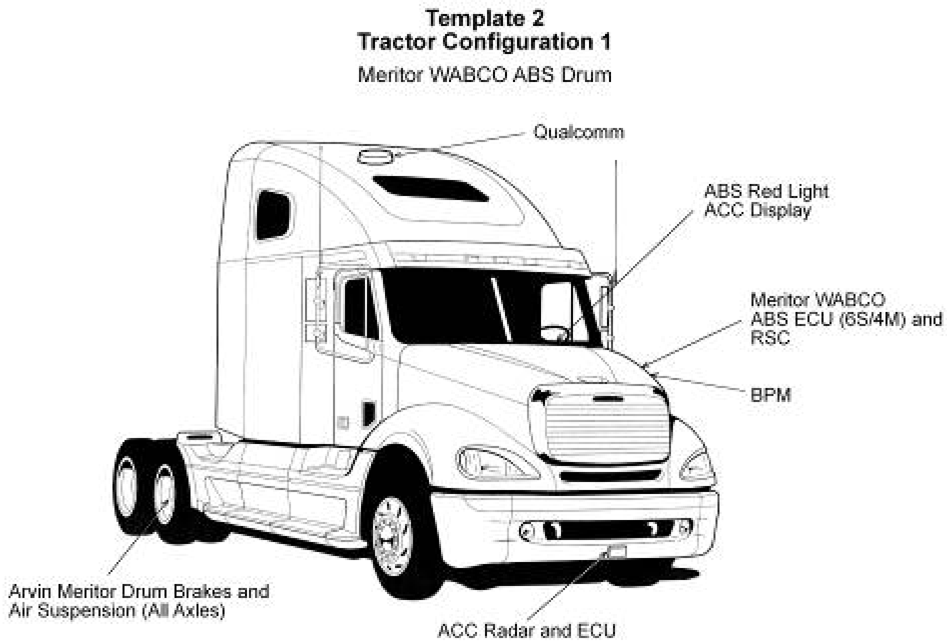


Figure 3-1. Template 2, Tractor Configuration 1: Meritor WABCO ABS Drum

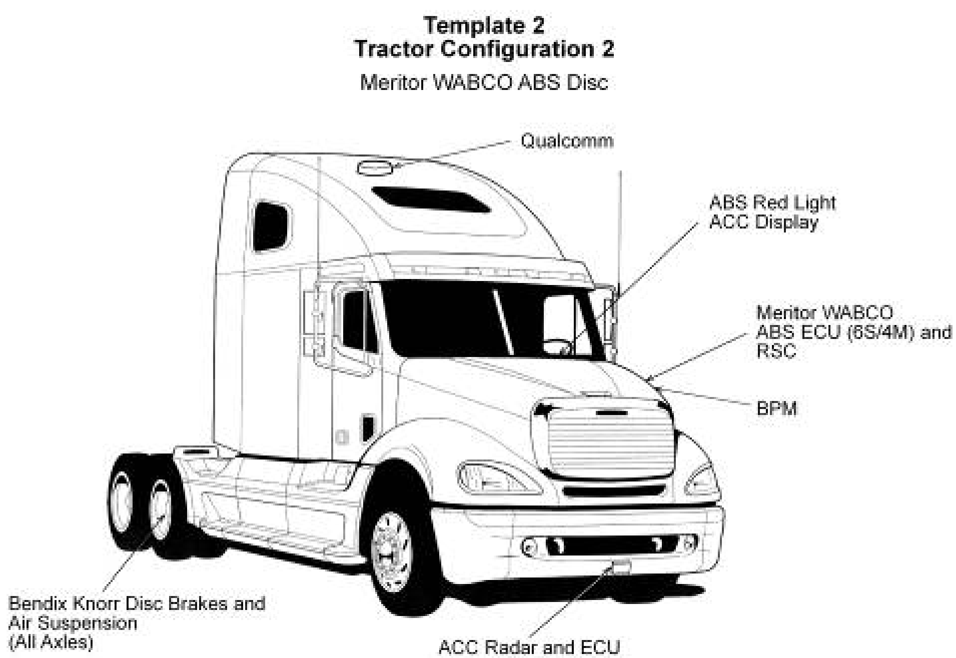


Figure 3-2. Template 2, Tractor Configuration 2: Meritor WABCO ABS Disc

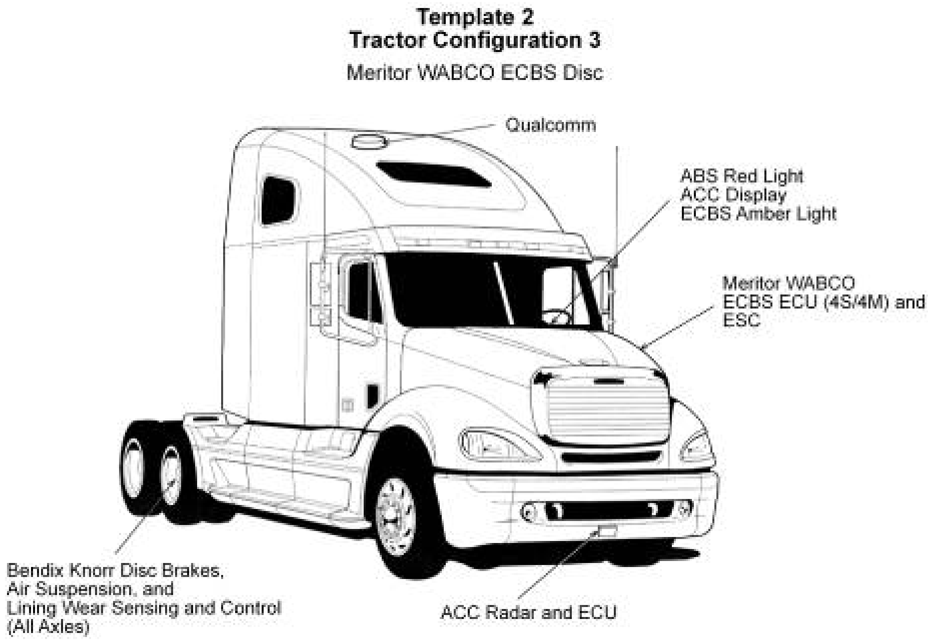


Figure 3-3. Template 2, Tractor Configuration 3: Meritor WABCO ECBS Disc

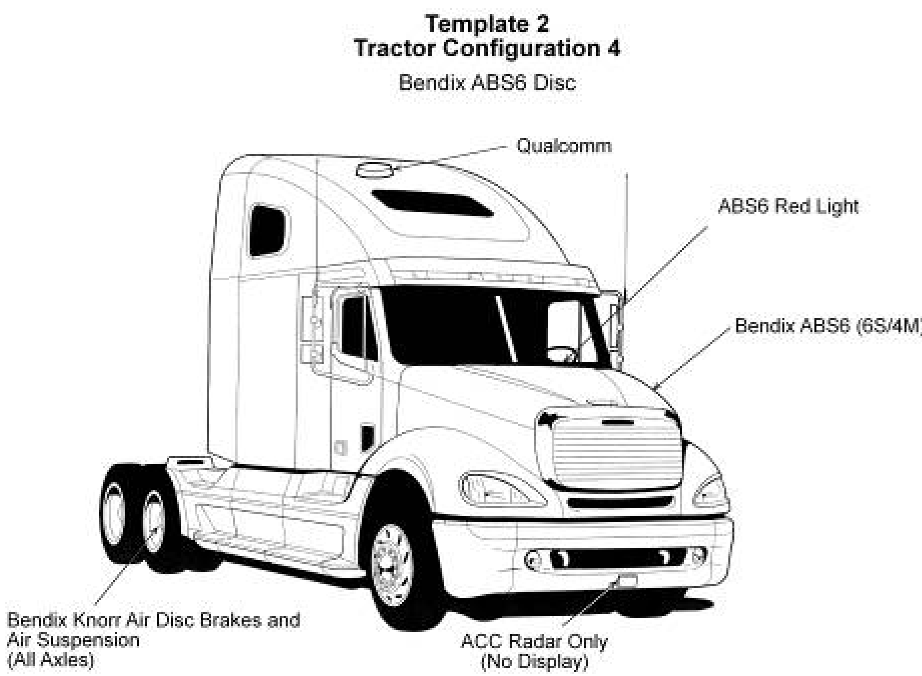


Figure 3-4. Template 2, Tractor Configuration 4: Bendix ABS6 Disc

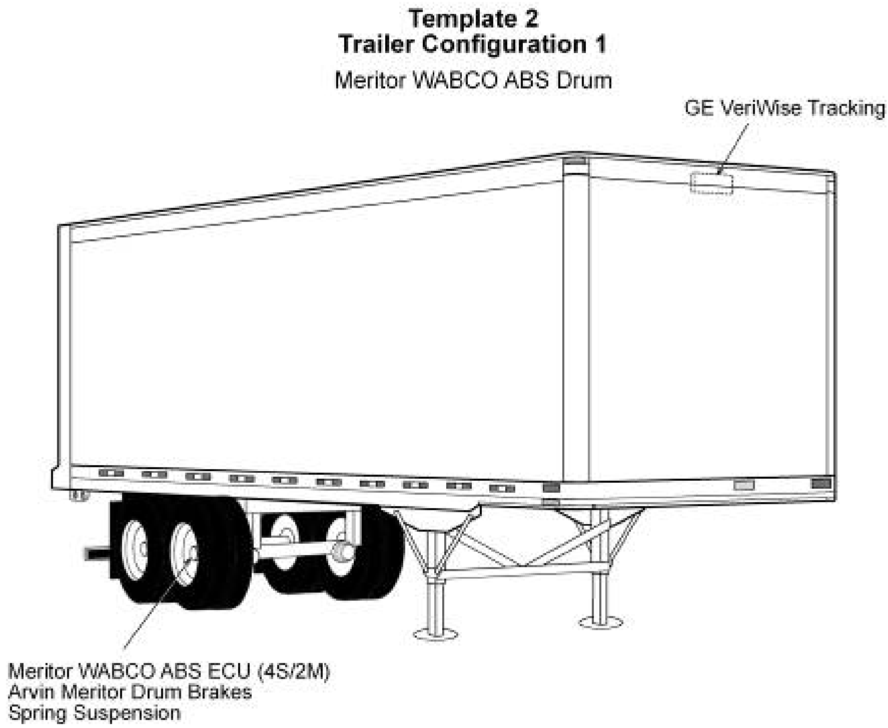


Figure 3-5. Template 2, Trailer Configuration 1: Meritor WABCO ABS Drum

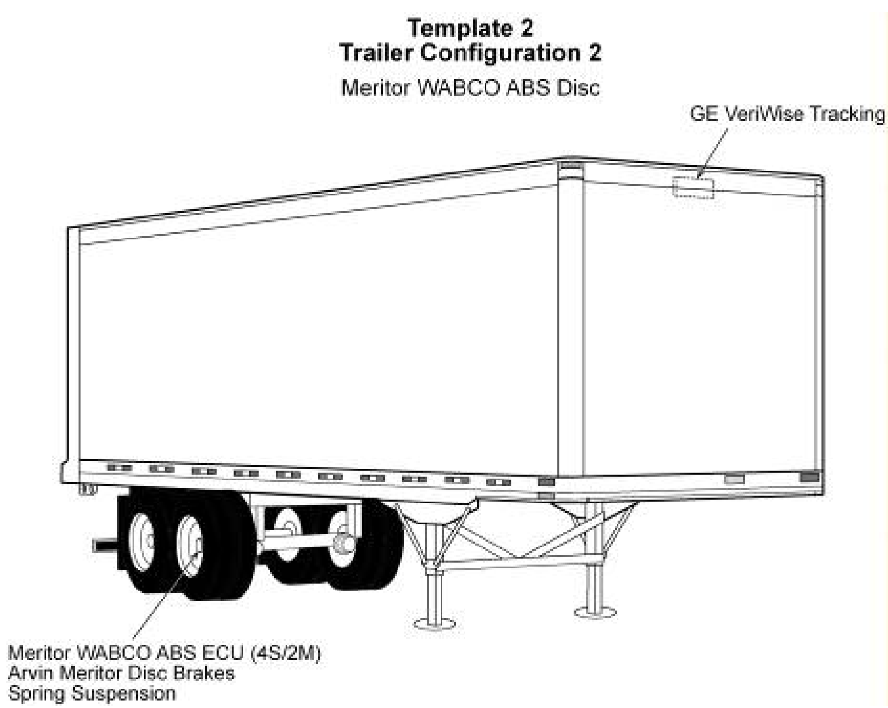


Figure 3-6. Template 2, Trailer Configuration 2: Meritor WABCO ABS Disc

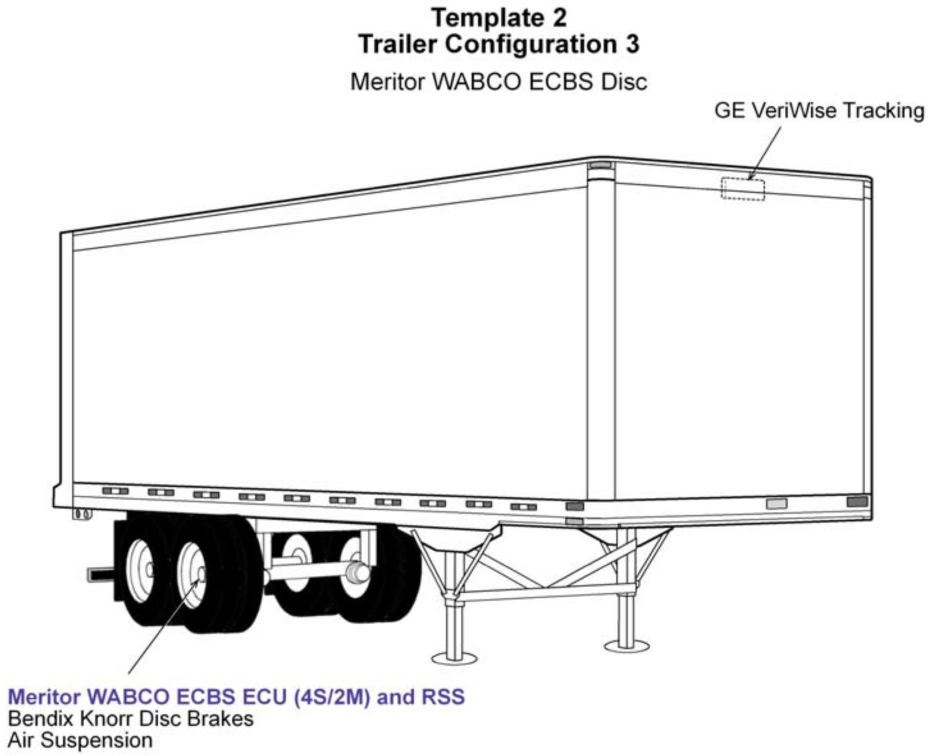


Figure 3-7. Template 2, Trailer Configuration 3: Meritor WABCO ECBS Disc

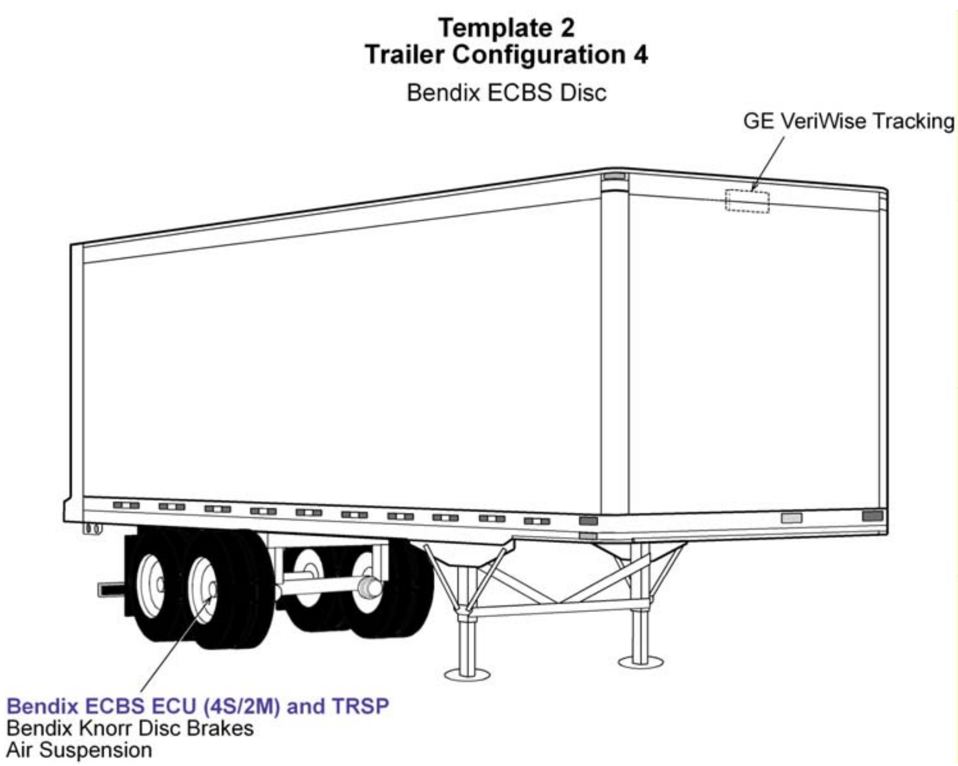


Figure 3-8. Template 2, Trailer Configuration 4: Bendix ECBS Disc

Table 3-2. Quantities and Specifications of Tractors and Trailers (Template 2)

TRACTOR			TRAILER		
Configuration	**#**	**Technologies**	**Configuration**	**#**	**Technologies**
Configuration 1 "MW ABS drum" T2C1	10	WABCO ABS (6S/4M) Meritor drum brakes ACC[1]** RSC[2]** BPM[3]	**Configuration 1 "MW ABS drum" T2C1**	15	WABCO ABS (4S/2M) Meritor drum brakes
Configuration 2 "MW ABS disc" T2C2	10	WABCO ABS (6S/4M) Bendix disc brakes ACC[1]** RSC[2]** BPM[3]	**Configuration 2 "MW ABS disc" T2C2**	15	WABCO ABS (4S/2M) Arvin Meritor disc brakes
Configuration 3 "MW ECBS disc" T2C3	10	Meritor WABCO 1E/2P ECBS (4S/4M) Bendix disc brakes ACC[1]** ESC[5]** LWS & C[6]	**Configuration 3 "MW ECBS disc" T2C3**	15	Meritor WABCO 1E/1P ECBS (4S/2M) Bendix disc brakes[4] RSS[7]**
Configuration 4 "BDX ABS6 disc" T2C4	10	Bendix ABS6 (6S/6M) Bendix disc brakes	**Configuration 4 "BDX ECBS disc" T2C4**	15	Bendix 1E/1P ECBS (4S/2M) Bendix disc brakes[4] TRSP[8]**
Total	40		**Total**	60	

MW Meritor WABCO BDX Bendix
1 ACC Adaptive cruise control, with service brakes (Meritor WABCO)
2 RSC Roll stability control, with service brakes (Meritor WABCO)
3 BPM Brake performance monitoring
4 Trailers with Bendix disc brakes were equipped with an air suspension. Configurations 1 and 2 trailers were equipped with spring suspension.
5 ESC Electronic stability control (Meritor WABCO)
6 LWS & C Lining wear sensing and control
7 RSS Roll stability support (Meritor WABCO)
8 TRSP Trailer Roll Stability Program™ (Bendix)

** Indicates enabled technologies.

Vehicle Instrumentation

Since, in this Template, tractors and trailers would be randomly assigned to each other, each vehicle was instrumented and equipped with a self-contained DAS. As such, data were collected on the trailers independently of the data collected on the tractors, and vice-versa, at any given time in Template 2. The data were acquired continuously at a fixed sampling rate of 10 Hz. The vehicle dynamics of a loaded tractor-trailer typically exhibit a sufficiently low frequency response that they can be adequately captured and studied with a 10-Hz data acquisition rate. Figures 3-9 and 3-10 illustrate the DAS as integrated on the Template 2 tractors and trailers. Additional details of the instrumentation, including sensors, wiring, and data compiling and storage, are provided in Appendix A.

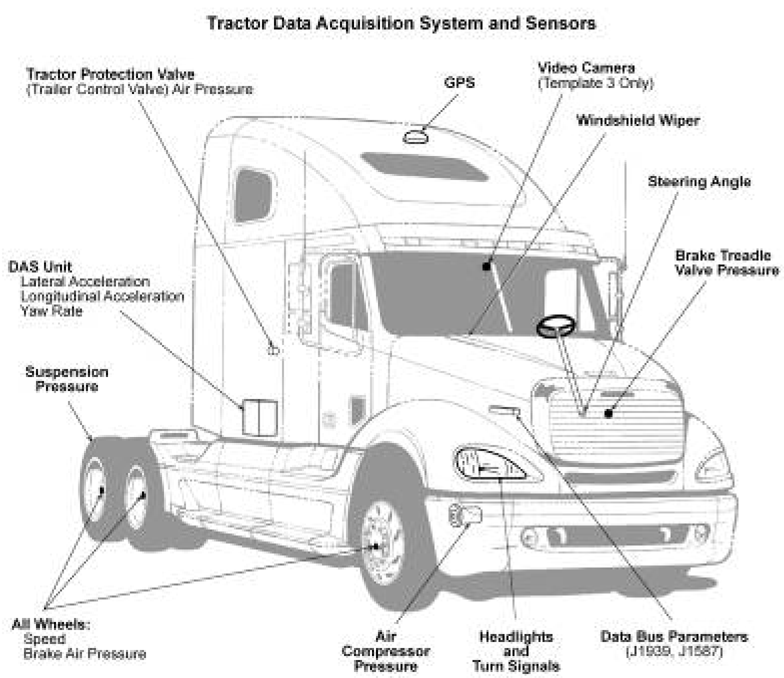


Figure 3-9. Schematic of DAS Installation on FOT Tractors

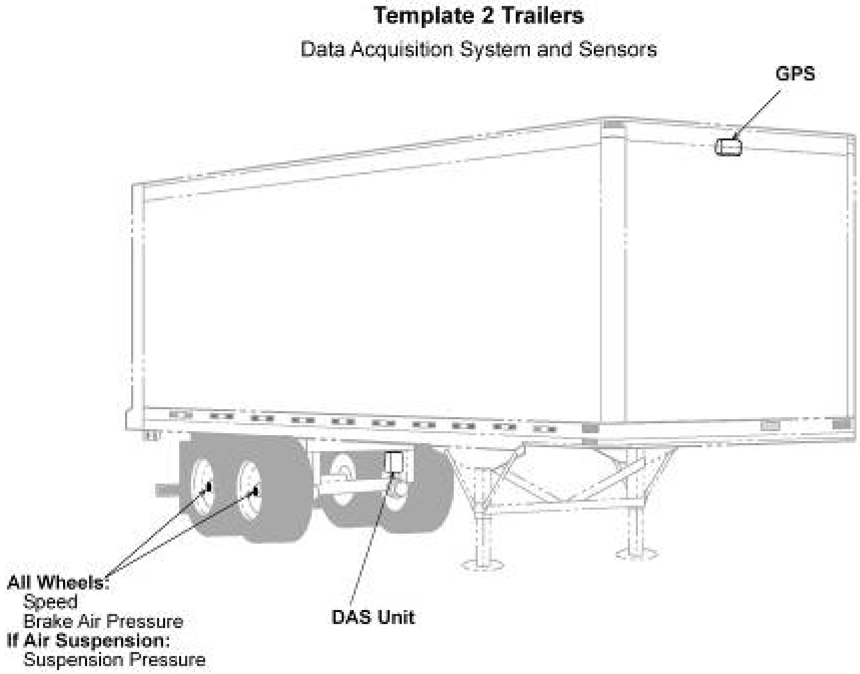


Figure 3-10. Schematic of DAS Installation on Template 2 Trailers

Data Collection Schedule and Test Phases

Figure 3-11 illustrates the Template 2 schedule for collecting data over a 12-month period. The data collection period was subdivided into two phases, beginning with a control phase in which normal driving performance data in the absence of advanced enabled safety technologies were recorded in each vehicle. As such, the data were collected to enable the comparative analyses of the ECBS versus ABS, and disc brakes versus drum brakes without the advanced safety technologies. These data also serve as control data for the analysis of advanced safety technologies. In the second phase of the data collection period, all enabled safety technologies were activated, hence permitting the evaluation of their combined potential safety benefits.

Based on the annual tractor mileage, the ratio of trailers to tractors, the number of vehicles in each group, and the duration of the data collection period, statistical analyses estimated that the total number of vehicle miles traveled (VMT) collected during the FOT would be sufficient to draw statistically significant conclusions.

Timeline

Phase 1	Phase 2
Foundation brakes & control systems are installed and ON: *ABS, ECBS, ABS6* *Drum, Disc Brakes* **Enabled Technologies ** are OFF**	**Foundation brakes & control systems are installed and ON:** *ABS, ECBS, ABS6* *Drum, Disc Brakes* **Enabled Technologies are ON:** *ACC* *RSC* *ESC* *RSS* *TRSP™*

Figure 3-11. Data Collection Schedule (Template 2)

Template 3: Matched Tractor-Trailer Combinations

In Template 3, tractors and trailers equipped with ECBS from the same vendor were paired to evaluate the performance and safety benefits of ECBS and enabled advanced safety systems.

Quantities and Specifications of Tractors and Trailers

The original solicitation required that tractors and trailers be equipped with ECBS from one supplier and be placed in an operating environment allowing ECBS vehicles to be operated in "married pair" combinations for 12 months. A "married pair" combination was defined as a combination in which a tractor and a trailer remain connected to each other during the day-to-day operations of the FOT. A control fleet was also required to allow comparison of the performance of ECBS versus non-ECBS vehicles. In addition, the original solicitation required that "Advanced Brake Safety System Components" designed to improve the vehicle's crash avoidance capability, i.e., advanced safety technologies, be installed on the vehicles.

The Freightliner Team equipped tractors and trailers with ECBS and advanced safety technologies, all provided by one vendor, Meritor WABCO. The Freightliner Team also installed disc brakes on all Template 3 tractors and trailers. The advanced safety technologies included:

- ACC
- ESC

- RSS
- LWS&C.

This configuration of tractors and trailers, referenced herein as "Template 3," was identical to Template 2, Configuration 3 tractors and trailers.

In addition, existing Wal★Mart tractors and trailers were included in the experimental design to provide baseline or profiling information on general driving behavior of the Template 3 drivers. These vehicles are referred to as "T3 baseline vehicles" in this report.

Figures 3-12 through 3-15 illustrate the brake-related technologies that were evaluated on T3 tractors and trailers, as well as the T3 baseline vehicles used for driver profiling. In these illustrations, the ECBS vehicles are labeled as "Configuration 3" and the baseline vehicles are labeled as "Configuration 0."

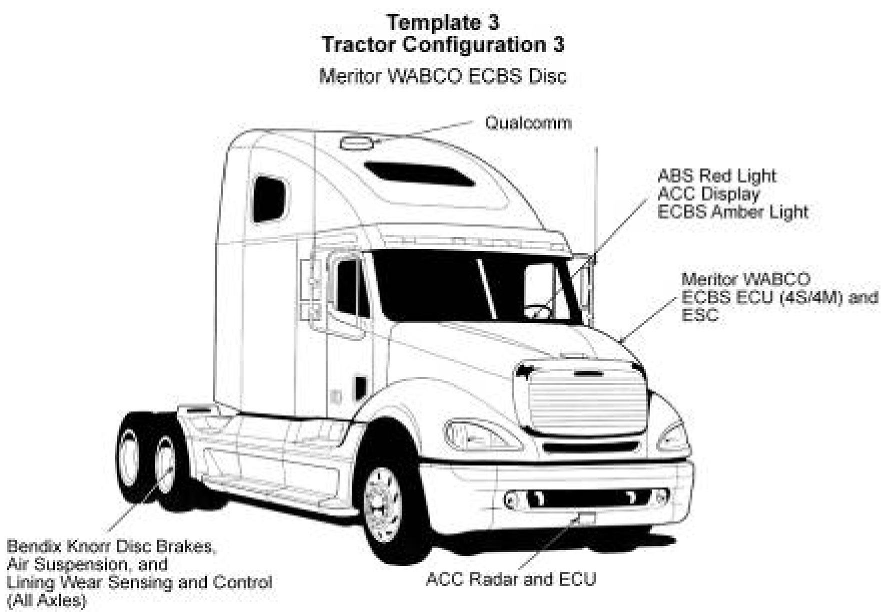


Figure 3-12. Template 3, Tractor Configuration 3: Meritor WABCO ECBS Disc

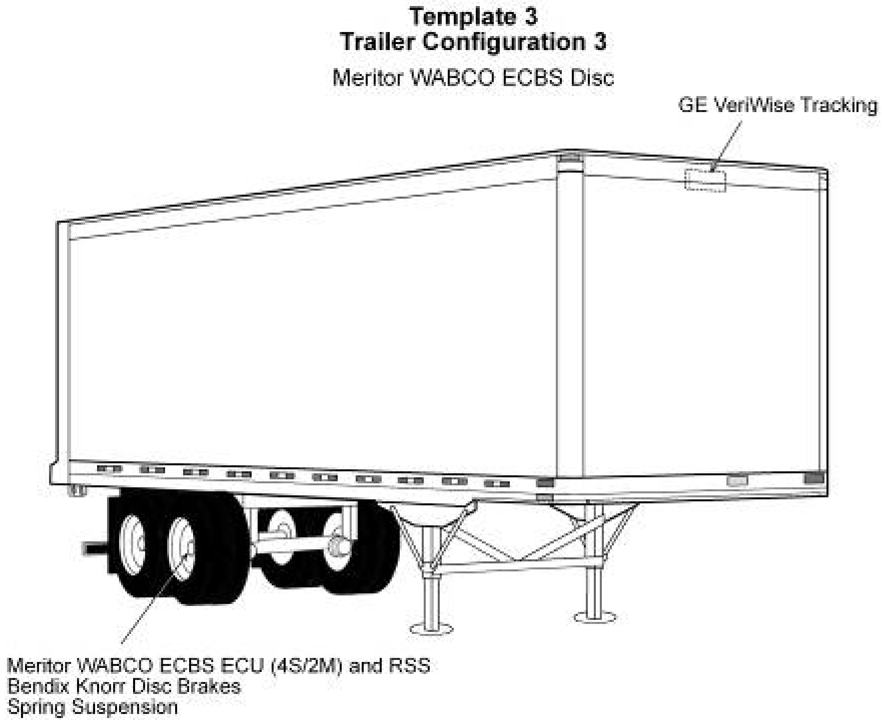


Figure 3-13. Template 3, Trailer Configuration 3: Meritor WABCO ECBS Disc

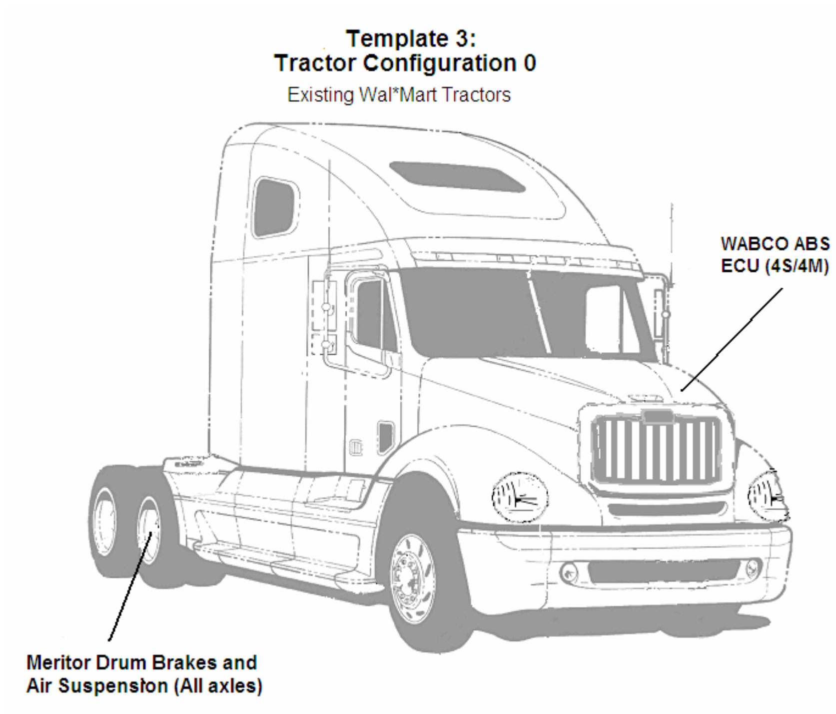


Figure 3-14. Template 3, Tractor Configuration 0: Existing Wal★Mart Tractors

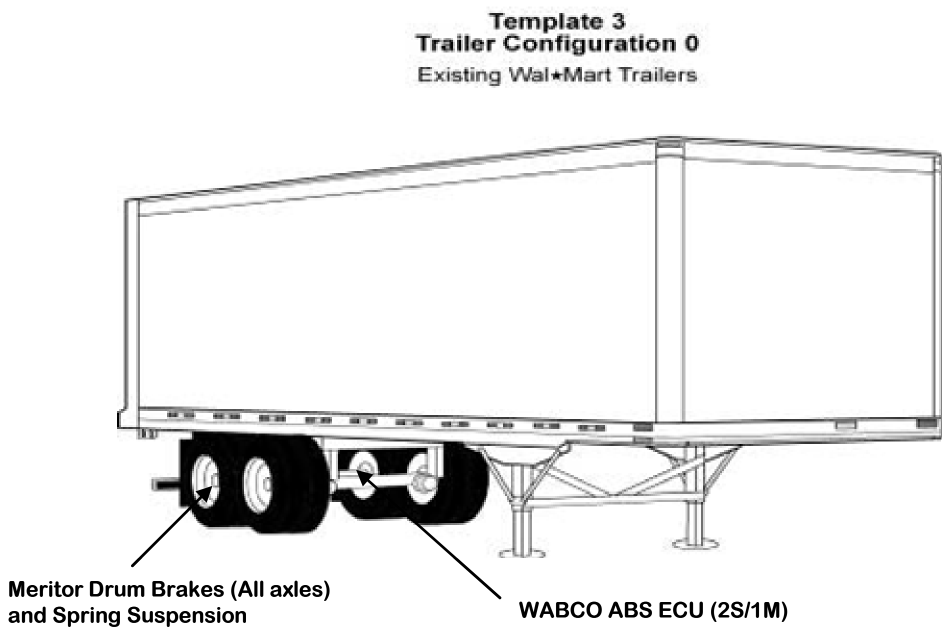


Figure 3-15. Template 3, Trailer Configuration 0: Existing Wal★Mart Trailers

Table 3-3 lists the specifications for the two configurations of tractors and trailers, as well as their corresponding quantities. A total of eight (8) existing Wal★Mart tractors, eight (8) ECBS tractors, and forty (40) ECBS trailers were instrumented and evaluated in this template. The ratio of FOT trailers to FOT tractors was increased to 5 to match the ratio of trailers to tractors in the Wal★Mart fleet and to satisfy the FOT requirements within the normal Wal★Mart "drop and hook" operations. Since Wal★Mart does not ordinarily operate tractors and trailers in "married" combinations, this increased ratio allowed each ECBS tractor to be always matched to an ECBS trailer (not necessarily the same trailer) during the 12-month data collection. To further facilitate vehicle matching, these Template 3 vehicles were operated on dedicated fixed routes as detailed later.

Vehicle Instrumentation

Template 3 tractors and trailers were instrumented with DASs developed by the Aberdeen Test Center. Since the vehicles were in matched pairs in this template, the data collected on the trailers were sent to the corresponding tractor's DAS unit for storage. As such, data from the tractors and trailers were retrieved simultaneously from the same device. In the event that the tractor was not connected to the trailer, or if the connector for data transfer between the trailer and the tractor was not in place, only tractor data were available. Baseline T3 tractors were also instrumented for data acquisition. Since driver profiling was the focus of the baseline data collection, trailers pulled by baseline tractors were not instrumented. Similarly to Template 2, the data were acquired continuously at a fixed sampling rate of 10 Hz. Figures 3-16 and 3-17 illustrate the DAS as integrated on the Template 3 tractors and trailers. Additional details of the instrumentation are provided in Appendix A.

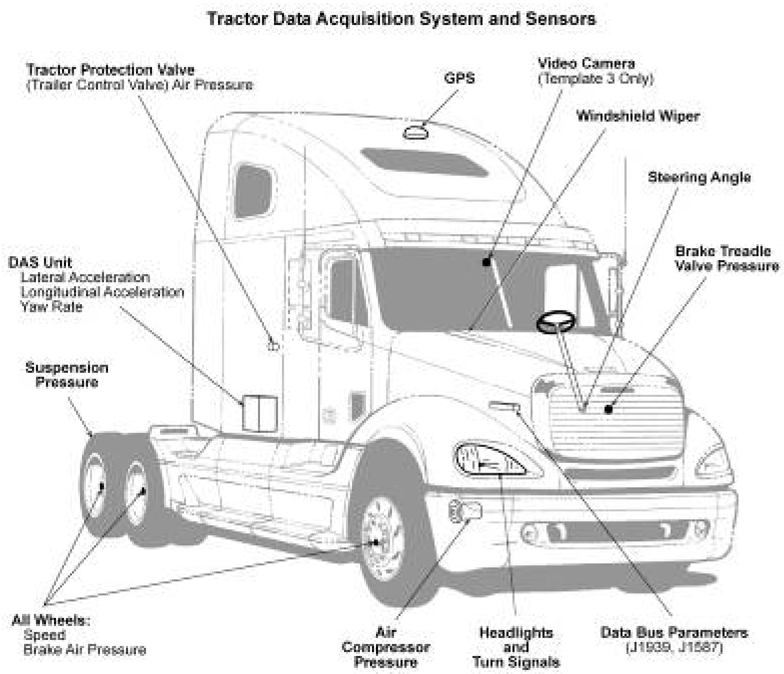


Figure 3-16. Schematic of DAS Installation on FOT Tractors

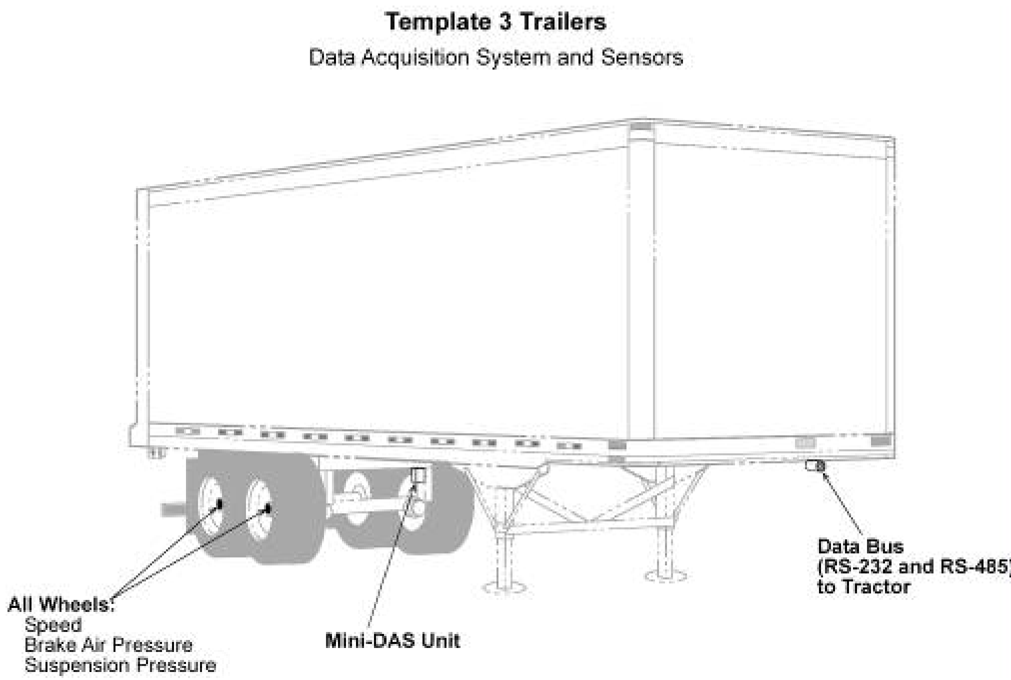


Figure 3-17. Schematic of DAS Installation on Template 3 Trailers

Data Collection Schedule and Test Phases

Figure 3-18 illustrates the Template 3 schedule for collecting data from baseline tractors and matched FOT combination vehicles over a 14-month period. The data collection period was divided into three phases: a driver baselining phase (Phase 0), an ECBS control phase (Phase 1), and an ECBS with enabled safety technology assessment phase (Phase 2).

Based on the annual tractor mileage, the ratio of trailers to tractors, the number of vehicles in each group, and the duration of the data collection period, statistical analyses estimated that the total number of VMT collected during the FOT would be sufficient to draw statistically significant conclusions.

Table 3-3. Quantities and Specifications of Tractors and Trailers (Template 3)

TRACTOR			TRAILER		
Configuration	**#**	**Technologies**	**Configuration**	**#**	**Technologies**
Configuration 0 "Driver baseline"	8	Existing Wal★Mart tractors: WABCO ABS Meritor drum brakes	**Configuration 0 "Driver baseline"**	n/a	Existing Wal★Mart trailers: WABCO ABS Meritor drum brakes
Configuration 3 "MW[5] ECBS disc" **T3**	8	Meritor Wabco 1E/2P ECBS (4S/4M) Bendix disc brakes ACC[1]** ESC[2]** Wear lining sensing & control	**Configuration 3 "MW[5] ECBS disc"** **T3**	40	Meritor Wabco 1E/1P ECBS (4S/2M) Bendix disc brakes[3] RSS[4]**

MW Meritor WABCO
1 ACC Adaptive cruise control, w/ service brakes (Meritor WABCO)
2 ESC Electronic stability control (Meritor WABCO)
** Indicates enabled technologies.
3 Trailers with Bendix disc brakes are equipped with an air suspension.
4 RSS Roll stability support (Meritor WABCO)

Timeline

Phase 0: Baselining Wal★Mart units	**Phase 1 FOT vehicles**	**Phase 2 FOT vehicles**
ABS, Drum Brakes	*ECBS, Disc Brakes* **Enabled Technologies ** are OFF**	*ECBS, Disc Brakes* **Enabled Technologies ** are ON** *ACC* *ESC* *RSS*

Figure 3-18. Data Collection Schedule (Template 3). Enabled Technologies are Indicated by (**).

3.1.2.2 Wal★Mart Operations

While the previous subsection provided information on the experimental design of the test (i.e., numbers of vehicles, types of vehicles, configurations of vehicles, data collected), this subsection summarizes elements of the fleet operations that are relevant to the test plan, i.e., elements that impacted the vehicle operation and data collection. Specifically, this section presents vehicle duty cycle, route characteristics, vehicle assignments, drivers' characteristics, and maintenance practices of the Wal★Mart fleet at the time of the FOT.

Wal★Mart operates a national fleet of tractors and semi-trailers for distribution of products and perishables. The fleet numbers more than 5,500 tractors, and 32,000 trailers. Wal★Mart averages 2,375,000,000 miles annually across the entire fleet and delivers to customers 24 hours a day, 7 days a week. On average, each tractor is driven approximately 125,000 miles annually, totaling 1,000,000 miles in 8 years. Operations are centralized around a given distribution center or terminal, therefore leading to dedicated, regional operations. The transportation department of Wal★Mart operates 38 distribution centers, each operating 135 tractors on average, up to a maximum of 300 tractors, and 800 to 1,400 trailers. The average trip includes deliveries to one or more of the 2,700 Wal★Mart stores, Wal★Mart Super Centers, and Sam's Club stores from and to one of the Wal★Mart distribution centers.

The field test involved naturalistic, day-to-day product delivery operations of Wal★Mart. Tractors operate out of a home distribution center and return to the base terminal upon completion of their local trips, hence facilitating regular collection of data. The tractors and trailers for this FOT were all placed in service in the Wal★Mart Loveland, Colorado, distribution center, located north of Denver, Colorado.

The geographic span of the field test was, at the time of the start of the FOT, an area around the terminal and defined by the locations of the trip destinations for delivery and/or pick-up. During the project, trip destinations were somewhat altered with the acquisition or reorganization of stores, hence making the service area dynamic. As shown on Figures 3-19 and 3-20, which illustrate the service area at the beginning of the FOT, the Wal★Mart fleet operates on a variety of routes (highways, urban roads, and/or country roads) in the mountainous region. As such, the frequency of brake applications observed on these vehicles was expected to be higher than that of interstate long-haul vehicles traveling through the Midwest.

All Template 2 vehicles were operated on similar road types, for similar average trip mileage and trip durations. Template 3 vehicles were operated on dedicated routes: each Template 3 tractor was assigned a specific route to predetermined dedicated locations. Figure 3-21 illustrates the location of dedicated stores within the service area around Loveland.

Each tractor is assigned to a given route for a minimum of six months. After six months, Wal★Mart re-assigns routes as directed by their operational needs or organizational factors. Most of Template 3 tractors remained assigned to dedicated routes for the duration of the FOT.

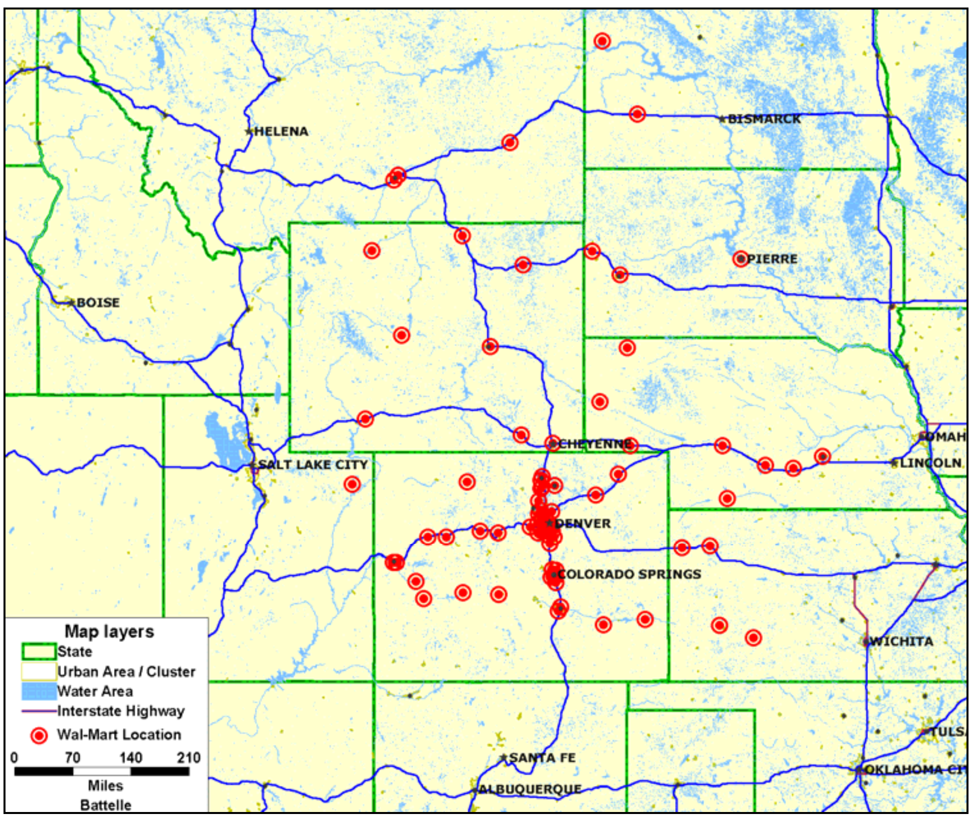


Figure 3-19. Wal★Mart Stores Defining the Service Area of the Wal★Mart Loveland (CO) Distribution Center: Geographic Span and Major Highways

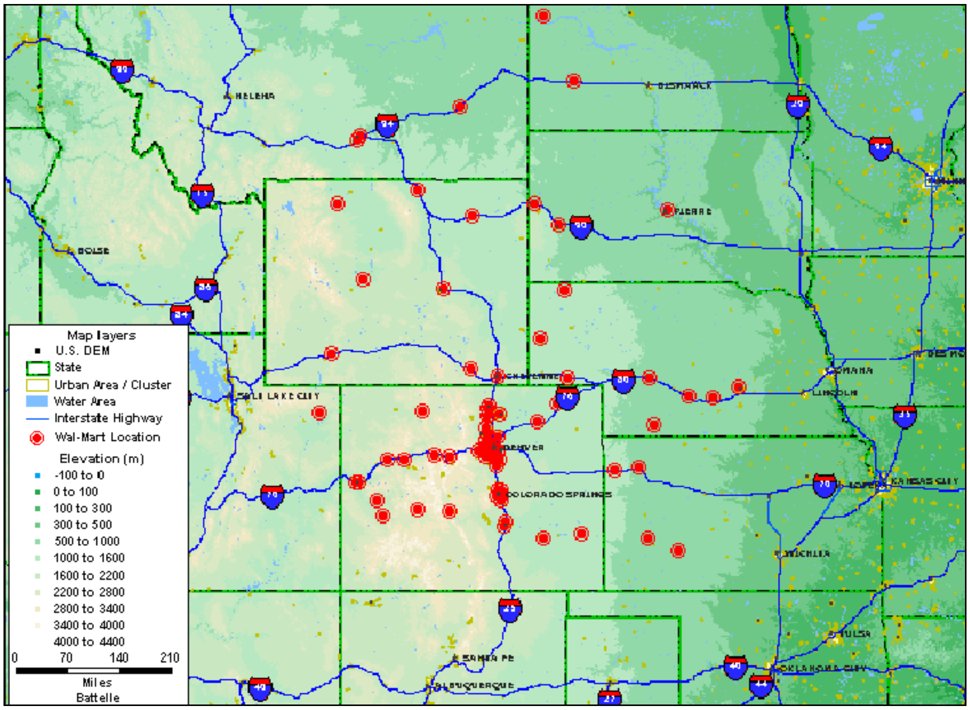


Figure 3-20. Wal★Mart Loveland (CO) Distribution Center: Geographic Span and Terrain

Figure 3-21. Dedicated Stores Serviced by the Wal★Mart Loveland (CO) Distribution Center, Defining Template 3 Routes

Wal★Mart operations are “drop and hook” operations: trailers are loaded while a given tractor is out on a trip delivering freight with another trailer. When the tractor finishes a given trip, the driver exchanges his empty trailer for a loaded trailer. In this type of operations, trailers are assigned to tractors in the Wal★Mart fleet on an as-needed basis, sometimes hourly, by the dispatch operational group, and a given tractor may not always be married to the same trailer. This type of operation is effective only when the number of trailers exceeds that of tractors, as is seen in the Wal★Mart fleet (5-to-1 ratio). Since the FOT vehicles were driven within the normal

Wal★Mart service operation, these observations were taken into consideration in the development of the experimental design of the FOT by setting the ratio of trailers to tractors to 1.5 and 5 in Template 2 and Template 3, respectively. In addition, to optimize the data collection process, all instrumented vehicles were tracked as they became part of sub-fleets, and the Wal★Mart fleet managers worked to match sub-fleet tractors to sub-fleet trailers.

Wal★Mart utilizes Qualcomm satellite communication systems, which allow communication and tracking of the tractor. Although it was not standard practice at Wal★Mart at the time of the FOT, tracking was implemented on the FOT trailers by the Freightliner Team, to facilitate FOT tractor-FOT trailer matching, and to ensure that no vehicle was lost or left the distribution center region. Untethered tracking systems were implemented on each trailer in this field test using the GE TIP satellite-based trailer tracking service with web access.

Wal★Mart has a retention rate for drivers that is well above the industry norm; the average driver in this investigation has been driving for Wal★Mart for 14 years. At the Loveland terminal, each driver is assigned to a specific tractor and only occasionally drives others. Under rare circumstances when the assigned tractor is unavailable, a driver may temporarily drive another driver's tractor for short durations. Drivers were assigned to the FOT tractors per normal fleet procedures without any intentional bias: drivers who needed a new tractor at the time of the FOT were assigned to any one of the FOT tractors.

Operations are organized around the clock, with no specific company restrictions on start/stop times other than those imposed by orders and loads to be delivered. Route assignments were made among the fleet of FOT vehicles per normal fleet procedures to satisfy fleet operational needs, without biased route assignments. In Template 3, vehicle/driver pairs were assigned to pre-defined routes, i.e., dedicated routes, per normal Wal★Mart processes.

To track and record vehicle maintenance parts, labor, and cost data, Wal★Mart utilizes Fleet Assistant, a software product originally developed by Freightliner. Fleet Assistant is a complete fleet management application designed to help companies easily organize all maintenance and repair information, schedule maintenance, and track vehicle life cycle costs using American Trucking Associations (ATA) maintenance codes.

3.1.2.3 Data Collection and Data Management

As detailed in the final test plan (Freightliner 2005), the data collected in this FOT included the following:

- **Onboard driving data.** Data relevant to brake system performance and safety-related vehicle dynamics were recorded continuously on the vehicles throughout the FOT.
- **Brake and tire-related maintenance data.** Relevant Wal★Mart maintenance records were collected and provided to the IE for use in estimating the reliability, performance, and costs associated with the new technologies with respect to conventional technologies.
- **Surveys.** Drivers and mechanics were questioned to seek their opinions on the reliability, maintainability, and safety impacts of the new systems.

These data sets are discussed in more detail in the following sections.

3.2 Task 2: "Assemble Test Vehicles with Electronically Controlled Braking System (ECBS)" and Task 3: "Conduct ECBS and Data Acquisition System (DAS) Checkout Testing"

3.2.1 Description of Work Performed

This section of the final report describes in detail the FOT preparation and checkout activities that took place prior to the start of the data collection period. Activities were carried out to:

- Prepare the vehicles for the field test, including installation, integration, and checkout of the vehicle safety technologies and the instrumentation in each vehicle platform
- Develop and set up the infrastructure and processes needed for data collection and management, including logistics and plans for transferring, storing, and validating the data collected
- Prepare for the FOT to be conducted in the fleet operations, including developing training material for the drivers and mechanics, developing support materials and processes, and understanding driver assignments.

The Freightliner Team selected a stepwise approach to prepare the vehicles for the FOT. Indeed, to maximize the successful implementation of systems and instrumentation on the vehicles, the Freightliner Team developed and tested systems (technologies and instrumentation) on pilot vehicles in advance of the construction of the FOT tractors and trailers for service. Following activities on the pilot vehicles, the Freightliner Team built and instrumented FOT vehicles. In parallel, the Freightliner Team also instrumented existing Wal★Mart tractors to collect baseline driver information in Template 3. Details of activities are presented below.

In parallel with preparation of the vehicles, the Freightliner Team prepared the infrastructure and processes for data management.

3.2.2 Pilot Tractors and Trailers

Pilot vehicles were built or retrofitted with advanced brake technologies, and instrumented by the Freightliner Team in Task 2. Table 3-4 lists the pilot vehicles included in the program along with their characteristics. The build/retrofit of pilot vehicles was combined with detailed development and testing activities (Task 3) to enhance systems integration and minimize risks of data loss.

3.2.2.1 Develop Specifications, Build Plans, and Instrumentation Plans

Specifications and build plans were developed for each type of tractor and trailer to be built for the FOT by the vehicle manufacturers. Configuration 1 vehicles did not require significant adjustments to the current specifications and build plans used for delivering vehicles to Wal★Mart, because these vehicles were intended to be control vehicles for the evaluation. Specifications and build plans of the other configurations of vehicles were adjusted to account for the integration of the safety technologies or for instrumentation implementation. For example, at the time of the vehicle design, the Bendix disc brake proposed for installation on the trailers (Template 2 configurations 3 and 4, Template 3) was only available for a trailer also equipped with an air suspension. As such, the specifications were modified to include air suspensions for the trailers equipped with ADB manufactured by Bendix. Specifications were also modified for instrumentation purposes. For example, on tractors equipped with a 4S/4M ABS (Template 2 configuration 2 and Template 3 tractors), wheel speed sensors were installed on the intermediate axle wheels.

Table 3-4. Quantities and Specifications of Pilot Tractors and Trailers (Template 3)

#	Tractors	Year, Make	Existing / New Build	Build / Retrofit Date	Residence
1	MW ECBS (Wal★Mart Spec) with disc brakes	2004, FTL Columbia	New	Dec. 2003	Troy, MI / TRC
2	Bendix ABS6 (Retrofit) with disc brakes	2003, FTL Century	Existing	Feb. 2004	Portland, OR
3	MW ECBS (Wal★Mart Spec) with disc brakes	2004, FTL Columbia	New	Nov. 2003	Portland, OR
4	MW ABS	2000, Kenworth T2000	Existing	N/A	Troy, MI / TRC
#	**Trailers**	**Year, Type**	**Existing / New Build**	**Build / Retrofit Date**	**Residence**
1	53ft Great Dane MW ECBS with disc brakes	2004, Wal★Mart	New	11/28/2003	Troy, MI / TRC
2	53ft Great Dane MW ECBS with disc brakes	2004, Wal★Mart	New	11/29/2003	Portland, OR
3	53ft Great Dane Bendix ECBS with disc brakes	2004, Wal★Mart	New	11/30/2003	Portland, OR
4	53ft Trailmobile MW ABS	2001, Flat bed	Existing	N/A	Troy, MI / TRC

MW Meritor WABCO BDX Bendix

Instrumentation plans were developed based on requirements set forth in the test plan (Freightliner 2005) to meet the project objectives. The pilot tractors and trailers were instrumented with the DAS and associated sensors planned to be used on the FOT vehicles. To facilitate checkout activities, the ECBS trailer (pilot trailer #2) was instrumented such that both T2 and T3 instrumentation could be validated. Details of the instrumentation are included in the section discussing the final instrumentation as implemented on FOT tractors and trailers.

3.2.2.2 Build and Assemble Pilot Tractors and Trailers

Four pilot tractors were manufactured or retrofitted by Freightliner following build guidelines developed by the Freightliner engineering team and the brake suppliers. Similarly, four pilot trailers were manufactured in the Great Dane production plant following guidelines developed by the Great Dane engineering team and the brake suppliers.

3.2.2.3 Instrument Pilot Tractors and Trailers

In parallel with installation and validation of all technologies on the pilot tractors and trailers, Battelle and the Aberdeen Test Center instrumented the vehicles and validated the systems. Personnel from the Aberdeen Test Center, Meritor WABCO, and Battelle traveled to the Freightliner Test Center in Portland, Oregon, for instrumentation of pilot vehicles. By first installing the instrumentation on the pilot vehicles, the team was given the opportunity to test the layout of the various components of the instrumentation and to investigate systems integration issues prior to implementation on actual FOT vehicles.

A full DAS box was installed on the pilot tractor and was loaded with Template 2 and Template 3 configuration files. The tractor was also instrumented with the appropriate hardware to allow the tractor to be configured as a Template 2 or Template 3 tractor. The trailer was also wired to accommodate operation as a Template 2 or a Template 3 vehicle. The lists below summarize the various sources of data that were wired into the DAS boxes of the tractor and trailer.

Pilot Tractor Instrumentation

- Curbside Front Brake Pressure Transducer
- Curbside Intermediate Brake Pressure Transducer
- Curbside Rear Brake Pressure Transducer
- Roadside Front Brake Pressure Transducer
- Roadside Intermediate Brake Pressure Transducer
- Roadside Rear Brake Pressure Transducer
- Trailer Protection Valve Pressure Transducer
- Air Compressor Pressure Transducer
- Suspension Air Bag Pressure Transducer
- Accelerometer (Longitudinal and Lateral)
- Yaw Rate Gyro
- Steering Angle Sensor
- J1939 bus data
- J1708/J1587 bus data
- Wipers, Lights, and Turn Signals
- GPS
- ACC radar (connected to J1939 bus)

Pilot Trailer Instrumentation

- Curbside Front Brake Pressure Transducer
- Curbside Rear Brake Pressure Transducer
- Roadside Front Brake Pressure Transducer
- Roadside Rear Brake Pressure Transducer
- Curbside Front Wheel Speed Sensor
- Curbside Rear Wheel Speed Sensor
- Roadside Front Wheel Speed Sensor
- Roadside Rear Wheel Speed Sensor
- Accelerometer (Longitudinal and Lateral)
- Yaw Rate Gyro
- Trailer ID Hard-Wired Into Connector
- Global Positioning System (GPS)
- Suspension Air Bag Pressure Transducer

When the tractor and trailer were intended to operate as Template 2 vehicles, the Template 2 configuration file was selected to run in the tractor DAS and a separate full DAS was installed on the trailer. In the case where the tractor and trailer were intended to operate in a Template 3 configuration, the Template 3 configuration file was selected to run in the tractor DAS and a mini-DAS was installed on the trailer. For Template 3 operation, it was also necessary to connect the RS232/RS485 wiring from the trailer to the tractor so that the trailer's mini-DAS could send data to the DAS on board the tractor.

Quality control (QC) checklists were drafted and used to verify that all hardware and associated wiring were in place on the tractor and trailer to allow the vehicles to operate as Template 2 or Template 3 vehicles.

3.2.2.4 Conduct Track and On-road Shakedown Testing of Pilot Vehicles

The FOT pilot tractors and trailers were subjected to a series of basic tests to confirm that, once placed in operational environments, the Wal★Mart vehicles would perform safely and reliably (Freightliner 2004b). When appropriate, data were collected from the onboard DAS to demonstrate that the instrumentation performed as required and that data collected would meet the needs of the IE for analysis. In addition to the basic driving tests, the pilot tractor-trailer combinations were operated in conditions similar to service conditions to allow final checkout and validation by the Team. As such, the Freightliner Team performed checkout testing at each critical step in the vehicle build and instrumentation process:

- Checkout of vehicles and advanced brake technologies on tractors and trailers: inspection of electrical connections and wiring harnesses for proper installation and connection, as well as operation of the systems to ensure proper performance
- Checkout of instrumentation on tractors and trailers: checking out the installation and connection of the DAS, as well as the functionality of data collection to ensure that the appropriate data were collected and stored properly
- Checkout of advanced brake systems and instrumentation on tractor-trailer combinations: inspecting combination vehicles in a service environment to verify functional

compatibility and to ensure that the overall vehicle construction is consistent with that of other standard vehicles delivered to the test fleet.

Tests conducted by the Freightliner Team included general driving tests as well as braking functionality and compatibility verification tests through pneumatic timing, pressure balance, stopping distance, ABS activation, and brake temperature balance tests (Appendix B). In addition to Freightliner's testing, brake system vendors or suppliers conducted additional functionality testing to demonstrate activation and performance of the FOT advanced systems such as RSS, TRSP, and ESC. The vendors conducted this testing as part of their validation and due diligence in delivering these new technologies to Freightliner and the marketplace. When appropriate, data from the FOT DAS were collected to checkout and validate instrumentation design. Data collected by the Freightliner Team were provided to the IE for evaluation, as appropriate.

3.2.2.5 Revise Vehicle Build and Instrumentation Plans

After building, instrumenting, and validating the safety technologies on the pilot vehicles, the Freightliner Team revised the vehicle specifications and build plans as appropriate for each configuration of vehicles in preparation for the FOT. The tractor and trailer build plans were then used for the remaining FOT vehicles. The Freightliner Team also developed a detailed instrumentation plan including QC procedures for instrumenting the FOT vehicles. Details of the QC procedures are included in the following sections.

3.2.3 FOT Vehicles: T3 Baseline Driver Profiling Tractors

3.2.3.1 Develop Instrumentation Plans

As detailed in the final test plan (Freightliner 2005), prior to collecting data on Template 3 FOT tractors and trailers, the conductor team collected selected data on eight Wal★Mart tractors in service at the time and driven by the T3 drivers prior to their transfer to their new tractors at the start of the FOT data collection period. Hardware was installed on the vehicles for the sole purpose of collecting profiling or baseline information on the driving characteristics of each driver prior to being exposed to a new tractor equipped with disc brakes and ECBS. As such, a smaller set of data parameters was of interest and only a subset of the pilot tractor instrumentation was installed on these tractors.

Figure 3-22 illustrates a layout of the instrumentation installed on the profiling tractors. A DAS unit was located outside the cab of the vehicle to collect and store data acquired from sensors and vehicle data buses. The DAS units included a 2-axis accelerometer and a yaw rate gyro to collect the longitudinal/lateral accelerations and yaw rate of the vehicle, respectively. A GPS unit was installed near the Qualcomm antenna of the vehicle and wired to the DAS unit to collect GPS location as well as time. A Meritor WABCO radar unit was installed on the front bumper of the vehicle and its ECU was wired to the DAS unit to collect vehicle tracking information. Finally, the DAS unit was also connected to the vehicle data buses to collect J1939 and J1587 data parameters such as vehicle speed and odometer. Further technical information on the instrumentation hardware is detailed in Appendix A

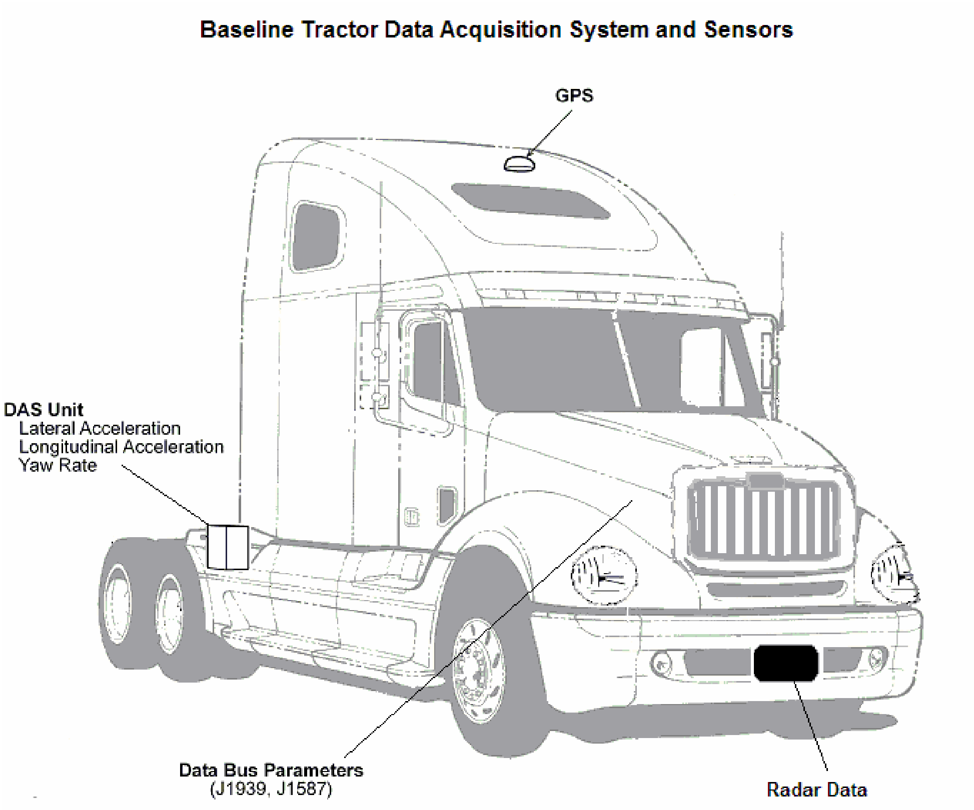


Figure 3-22. Schematic of DAS Installation on Baseline Tractors

The data parameters collected on the baseline tractors with this instrumentation include data collected from the vehicle data buses (e.g., vehicle identification number, or VIN, and speed), from the radar data bus (e.g., target range), from accelerometers located within the DAS unit (e.g., longitudinal and lateral acceleration) and from the GPS receiver. Data were stored in the data file either at the start of the data file (e.g., DAS ID) or at 10 Hz. Further details on the sources of the data collected (e.g., bus addresses) are included in Appendix C.

3.2.3.2 Instrument Profiling Tractors

The ACC radars and associated materials were provided by Meritor WABCO. The Aberdeen Test Center provided the DAS boxes that had been used in a previous FOT. Prior to arrival in Loveland for instrumentation of the profiling tractors, the Aberdeen Test Center also acquired GPS units and all other materials required to successfully complete the instrumentation activities.

Personnel from the Aberdeen Test Center, Meritor WABCO, and Battelle traveled to the Wal★Mart Distribution Center in Loveland for instrumentation of the eight International tractors that were used as driver profiling tractors. The eight tractors were outfitted with full DAS boxes, GPS, and ACC radar. The GPS was connected directly into the DAS, and the ACC was tied into the tractor’s J1939 bus. The existing J1587 and J1939 buses were wired into the DAS so that various tractor data, including ACC data, could be acquired. An existing connector in the tractor’s power distribution module was tapped for instrumentation power.

A QC checklist was developed and was closely followed to ensure that all instrumentation was properly installed (Appendix D). After it was determined that all instrumentation was properly installed, the tractors were given a final inspection and were each driven on short road tests to verify that accurate and complete data were being collected and that all instrumentation was operating as expected.

3.2.4 FOT Vehicles: Tractors

3.2.4.1 Build and Assemble FOT Tractors

The fleet FOT tractors were built following normal production processes of the Freightliner production lines according to Wal★Mart's fleet specifications and using guidelines from the finalized tractor build plans. Special considerations were taken for facilitating instrumentation of the tractors.

3.2.4.2 Instrument FOT Tractors

Once built, the tractors were instrumented according to the requirements of each truck's configuration by Battelle, the Aberdeen Test Center, and Meritor WABCO at the Freightliner Truck Manufacturing plant in Cleveland, North Carolina, in a building dedicated for this effort (Figure 3-23). Section 3.1.2.1 describes in generic terms the instrumentation plan and hardware utilized for each configuration of vehicle. Further details are provided in Appendix A.

Figure 3-23. Tractor Instrumentation in Cleveland, NC

Aberdeen Test Center provided the DAS boxes that had been used in a previous FOT and upgraded for this FOT. Prior to arrival in Cleveland, the Aberdeen Test Center acquired or built pressure transducers, steering angle sensors, wheel speed sensors, GPS units, harnesses, and all other materials required to complete the instrumentation activities. The ACC radars and associated materials were provided by Meritor WABCO. First, sensors and wiring were installed on the vehicles. Then connectors were pinned, and finally the DAS boxes previously subjected to static validation were installed. As detailed in Appendix A, a full DAS was installed on each tractor, each with the Template 2 or Template 3 configuration file, as appropriate.

Table 3-5 below provides a summary of the six different hardware configurations. A bullet symbol (●) in a cell indicates that the listed data source is present in that particular hardware configuration.

All instrumentation activities, from preparing the vehicle for instrumentation to the driving tests conducted upon final validation, were documented in checklists developed for QC purposes for each tractor configuration. These checklists, exceeding 30 pages, were maintained by engineers monitoring the instrumentation on site. QC checklists were closely followed by the instrumentation staff on site to ensure that all instrumentation was not only properly installed on each vehicle but also consistent from one vehicle to the other within each configuration. An example page from one of these checklists is shown in Figure 3-24. Detailed checklists are included in Appendix D.

The main objectives of the QC activities were to:

1) Ensure that every vehicle was instrumented in a consistent fashion
2) Provide a record of reference data for the installations
3) Document the installation so that it could be repeated in the future
4) Maintain tracking of progress when multiple vehicles were in various stages of completion
5) Ensure that accurate data were collected by the system upon completion of instrumentation.

Table 3-5. FOT Tractor Instrumentation

Instrumentation Components	T2C1	T2C2	T2C3	T2C4	T3
Full DAS	●	●	●	●	●
Curbside Front Pressure Transducer	●	●	●	●	●
Curbside Intermediate Pressure Transducer	●	●	●	●	●
Curbside Rear Pressure Transducer	●	●	●	●	●
Roadside Front Pressure Transducer	●	●	●	●	●
Roadside Intermediate Pressure Transducer	●	●	●	●	●
Roadside Rear Pressure Transducer	●	●	●	●	●
Trailer Protection Valve Pressure Transducer	●	●	●	●	●
Treadle Valve Pressure Transducer	●	●		●	
Air Compressor Pressure Transducer	●	●	●	●	●
Suspension Air Bag Pressure Transducer	●	●	●	●	●
Curbside Intermediate Wheel Speed Sensor			●		●
Roadside Intermediate Wheel Speed Sensor			●		●
Accelerometer (Longitudinal and Lateral)	●	●	●	●	●
Yaw Rate Gyro	●	●	●	●	●
Steering Angle Sensor	●	●		●	
J1939 bus data connections	●	●	●	●	●
J1708/J1587 bus data connections	●	●	●	●	●
Wipers, Lights, and Turn Signals connections	●	●	●	●	●
GPS receiver	●	●	●	●	●
ACC radar (connected to J1939 bus)	●	●	●	●	●
Video Equipment (Camera, Video DAS)					●

After all instrumentation was installed as detailed in the QC checklist, the tractors were given a final inspection and road test. In the road test, each tractor was driven around the Freightliner facility in a predefined route and subjected to a sequence of specific events (braking, turning, headlights on, etc.) to verify that the instrumentation was operating as intended and that data were collected accurately and completely. Figure 3-25 shows the road test course that was followed by each FOT tractor at the Freightliner plant. Instructions for the road tests are detailed in the QC checklist (Appendix D).

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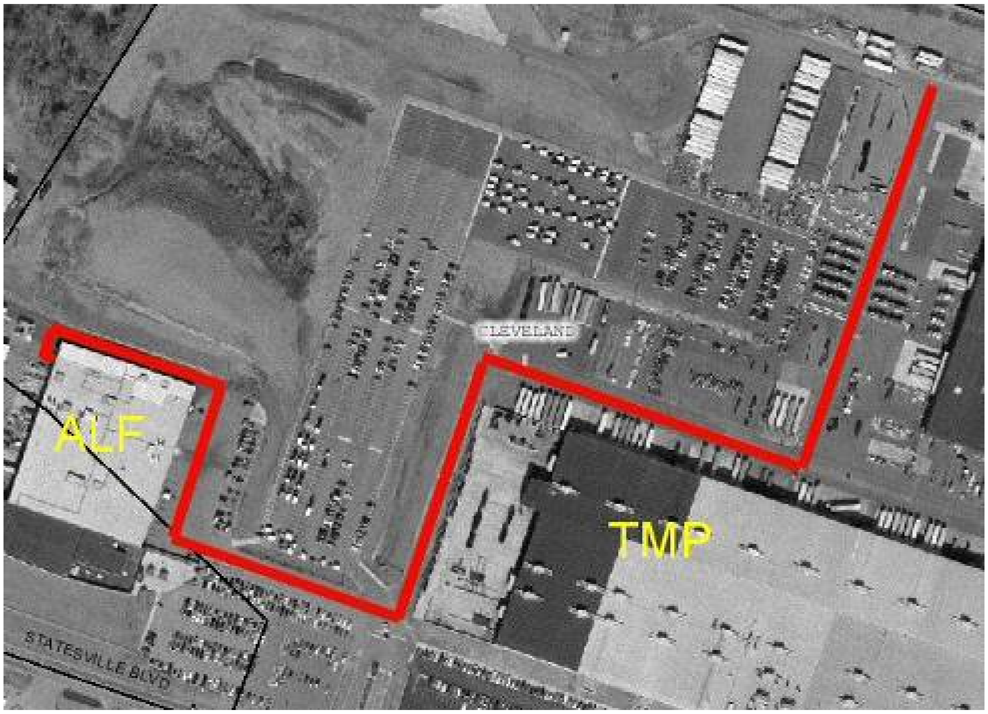
S/N__________________

Data Sheet D-1: T2C1 Tractor

	Work by/Date
pre-made cable	______/______
18.11 Route sensor cable along lefthand frame rail to cross-member at back of cab, over to righthand frame rail, on to DAS bulkhead connector location	______/______
19.0 Suspension Pressure Transducer - Roadside Rear	______/______
19.1 Remove supply pressure line from 90° fitting on suspension airbag	______/______
19.2 Remove 90° fitting from suspension airbag	______/______
19.3 Install street tee with pipe dope on airbag	______/______
19.4 Orient street tee such that the transducer will be parallel with the ground, pointed towards the front of the truck when installed	______/______
19.5 Connect 90° fitting to street tee with pipe dope	______/______
19.6 Connect pressure line to 90° fitting	______/______
19.7 Transducer: Measurement Specialties MSP400-150-P-N-4 (1/4" NPT)	______/______
19.8 Transducer S/N: ________________	______/______
19.9 Attach transducer to street tee with pipe dope	______/______
19.10 Apply and shrink heat shrink over bare wires exposed below connector on pre-made cable	______/______
19.11 Route sensor cable along lefthand frame rail to cross-member at back of cab, over to righthand frame rail, and on to DAS bulkhead connector location	______/______
20.0 Install Brake Chamber Pressure Transducer - Curbside Rear	______/______
20.1 Remove supply pressure line from 45° fitting attached to brake chamber	______/______
20.2 Remove 45° fitting from brake chamber	______/______
20.3 Install street tee with pipe dope on brake chamber	______/______
20.4 Orient street tee such that transducer will point upward	______/______
20.5 Attach 45° fitting to street tee with pipe dope	______/______
20.6 Connect pressure line to 45° fitting	______/______
20.7 Transducer: Measurement Specialties MSP400-150-P-3/8" NPT-4	______/______
20.8 Transducer S/N: ________________	______/______
20.9 Attach transducer to street tee with pipe dope	______/______
20.10 Apply and shrink heat shrink over bare wires exposed below connector on pre-made cable	______/______
20.11 Route sensor cable along righthand frame rail to DAS bulkhead connector location	______/______
21.0 Install Compressor Governor Signal Pressure Transducer	______/______
21.1 Remove pressure relief valve so that pressure supply line may be accessed	______/______
21.2 Remove compressor supply pressure line and fitting	______/______
21.3 Install street tee with pipe dope on compressor	______/______
21.4 Orient street tee such that transducer will point downward towards the road when installed	______/______
21.5 Connect pressure line and fitting to street tee	______/______
21.6 Connect pressure relief valve to compressor with pipe dope	______/______

QA review by ________________________________ Date_________

Figure 3-24. Example Page of a QC Checklist



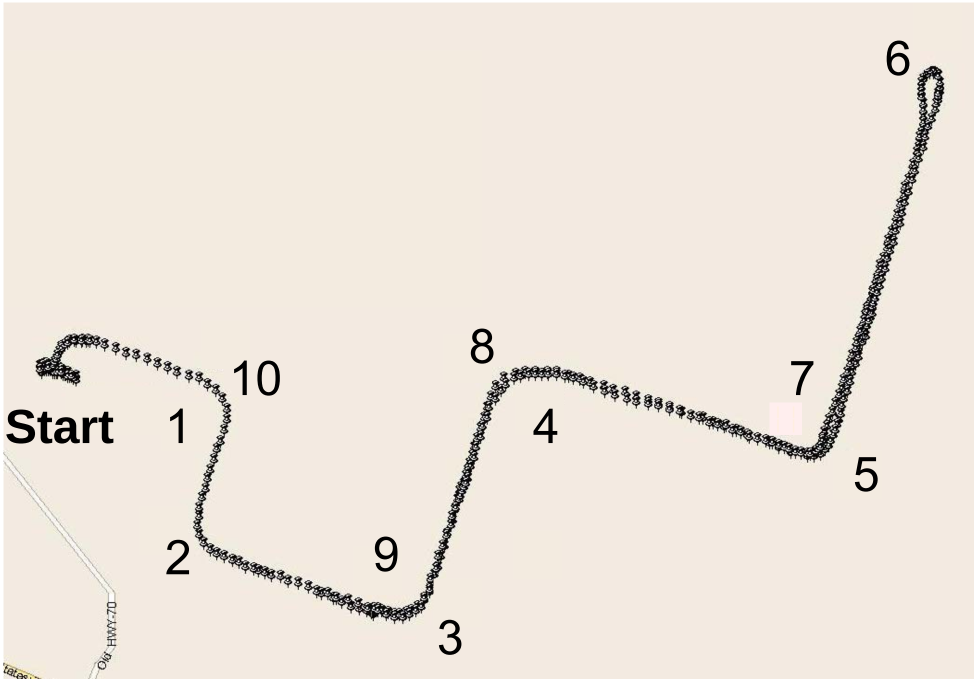


Figure 3-25. FOT Tractor QC Road Test Course

Figure note: ALF indicates the location where the vehicles were instrumented and the starting point of the road test; numbers indicate the road test checkpoints: (1) Stop, hard brake, right turn signal; (2) Left turn signal; (3) Low beams on; (4) High beams on; (5) All lights off; (6) U-turn; (7) Low wipers on; (8) High wipers on; (9) Wipers off; (10) Constant speed.

3.2.4.3 Validate and Deliver Equipped Instrumented Tractors to Wal★Mart

The build plan stated that all FOT vehicles, ECBS- or ABS-equipped, would be subjected to a thorough validation process by the Freightliner Team prior to delivery to the Wal★Mart fleet and commencement of field testing. As such, after instrumentation validation, the vehicles were inspected again by the Freightliner service group, as normally done for all Freightliner products, to prepare the vehicles for delivery to the customer. Tractors were transported in pairs. Data were recorded from the drive vehicle for the duration of the trip, hence providing validation data on cross-country operation for many consecutive hours of driving. Upon arrival in Loveland, the data cards were removed from the DAS and sent to Battelle for review. The Freightliner Team reviewed the data collected by all drive tractors in depth, identified deviations, and proposed appropriate fixes to the DAS software. Software changes were implemented in Loveland by the Aberdeen Test Center before the start of the FOT, by modifying the configuration file or the firmware loaded on DAS units on the respective vehicles.

3.2.4.4 USDOT / IE Briefing

A briefing was held in Cleveland, North Carolina, on October 6 and 7, 2004, with the USDOT, the IE, and members of the Freightliner Team, including Wal★Mart, Freightliner, Battelle, the Aberdeen Test Center, and Meritor WABCO. The status of the project was reviewed in depth, including review of vehicles built, vehicle instrumentation, data management process implementation, and fleet support development. The IE also presented the status of their activities. Briefing support slides were submitted to the USDOT after the meeting.

3.2.5 FOT Vehicles: Trailers

3.2.5.1 Build and Assemble FOT Trailers

The fleet FOT trailers were built following normal production processes of the Great Dane production lines according to Wal★Mart's fleet specifications and using guidelines from the finalized FOT trailer build plans. Special considerations were taken for facilitating instrumentation of the trailers as detailed in Table 3-6 below. For example, to optimize instrumentation of the trailers, Great Dane and Hendrickson installed pressure transducers at the brake chambers and additional wheel speed sensors at each wheel during production while Aberdeen Test Center/Battelle inspected and, as needed, repaired at a later time. All instrumentation hardware was provided by the Freightliner Team to the manufacturers.

Table 3-6. Instrumentation Activities Conducted by Great Dane, Hendrickson, and Battelle/Aberdeen Test Center

	Trailers with Spring Suspension	Trailers with Air Suspension	
	T2C1, T2C2	**T2C3, T2C4**	**T3**
Great Dane	Pressure transducers @ brake chamber	-	-
	Wheel speed sensors @ each wheel	-	-
	Wheel speed sensor wiring	-	-
	GPS antenna & bracket	GPS antenna & bracket	-
	GPS wiring	GPS wiring	-
	DAS mounting bracket	-	-
Hendrickson	-	Pressure transducers @ brake chamber	Pressure transducers @ brake chamber
	-	Pressure transducer @ air bag	Pressure transducer @ air bag
	-	Wheel speed sensors @ each wheel	Wheel speed sensors @ each wheel
	-	Wheel speed sensor wiring	Wheel speed sensor wiring
	-	DAS mounting bracket	DAS mounting bracket
Aberdeen Test Center/Battelle	P transducer wiring @ each brake chamber	P transducer wiring @ each brake chamber	P transducer wiring @ each brake chamber
	-	P transducer wiring @ air bag	P transducer wiring @ air bag
	DAS	DAS	DAS
	DAS wiring & connector pinning	DAS wiring & connector pinning	DAS wiring & connector pinning
	Inspect, replace, repair as needed	Inspect, replace, repair as needed	Inspect, replace, repair, as needed

Battelle traveled to the Great Dane manufacturing plant in Brazil, Indiana, to inspect instrumentation installed by Great Dane on spring suspension buggies and by Hendrickson on air suspension buggies before the box was installed. Battelle repaired, replaced, or installed, as appropriate, any additional sensors and wiring as needed prior to final assembly of the trailers. Integration of selected instrumentation activities at the time of manufacture yielded more consistent and reliable installation of the instrumentation components in the trailers. GE TIP representatives also traveled to the Great Dane manufacturing plant to install and initiate the trailer tracking hardware. Upon final assembly and inspections, the trailers were then shipped to Loveland, Colorado, for customer delivery.

3.2.5.2 Instrument FOT Trailers

The trailers' instrumentation was completed by the Aberdeen Test Center and Battelle at the Wal★Mart Distribution Center in Loveland, Colorado, according to the requirements of each template. Trailer instrumentation was similar to tractor instrumentation detailed in previous sections (instrumentation plan and hardware), with components slightly varying between configurations. Details are provided in Appendix A.

The Aberdeen Test Center provided the full DAS boxes (Template 2), the mini-DAS boxes (Template 3), and any wiring and components that were not installed on the trailers during assembly (e.g., connectors, pins, etc.). First, sensors and wiring previously installed were inspected to ensure that no damage had occurred from transport (Table 3-6). Then, appropriate sensors and wiring were added, connectors were pinned, and finally the DAS boxes previously subjected to static validation were installed. As detailed in Appendix A, a full DAS was installed on each Template 2 trailer, each with the Template 2 trailer configuration file, while a mini DAS was installed on each Template 3 trailer.

Table 3-7 summarizes the various instrumentation components (sources of data) that were wired into the DAS of the Template 2 trailers and into the mini-DAS of the Template 3 trailers.

Table 3-7. FOT Trailer Instrumentation

Instrumentation Components	T2C1	T2C2	T2C3	T2C4	T3
Full DAS	●	●	●	●	-
Mini DAS	-	-	-	-	●
RS232/RS485 wiring	-	-	-	-	●
Curbside Front Trailer Pressure Transducer	●	●	●	●	●
Curbside Rear Trailer Pressure Transducer	●	●	●	●	●
Roadside Front Trailer Pressure Transducer	●	●	●	●	●
Roadside Rear Trailer Pressure Transducer	●	●	●	●	●
Suspension Air Bag Pressure Transducer	-	-	●	●	●
Curbside Front Trailer Wheel Speed Sensor	●	●	●	●	●
Curbside Rear Trailer Wheel Speed Sensor	●	●	●	●	●
Roadside Front Trailer Wheel Speed Sensor	●	●	●	●	●
Roadside Rear Trailer Wheel Speed Sensor	●	●	●	●	●
Accelerometer (Longitudinal and Lateral)	●	●	●	●	●
Yaw Rate Gyro	●	●	●	●	●
GPS Receiver	●	●	●	●	-

The detailed list of data collected from the FOT trailers is included in Appendix C.

QC checklists (Appendix D) were developed and were closely followed to ensure that all instrumentation was properly installed. A separate set of procedures was created for each different type of trailer. These checklists, which were similar to that shown in the example in Figure 3-24 above, exceeded 10 pages and were maintained by Battelle engineers monitoring the instrumentation on site.

The main objectives of the QC activities were to:

1) Ensure that every vehicle was instrumented in a consistent fashion
2) Provide a record of reference data for the installations
3) Document the installation so that it could be repeated in the future
4) Maintain tracking of progress when multiple vehicles were in various stages of completion
5) Ensure that accurate data were collected by the system upon completion of instrumentation.

After all instrumentation was installed as detailed in the QC checklist, the trailers were given a final inspection and short road test. In the road test, each trailer was pulled by an instrumented tractor around the Wal★Mart terminal on a predefined route and subjected to a sequence of specific events (e.g. braking) to verify that the instrumentation was operating as intended and that data were collected accurately and completely. Details on the road test conducted are included in Appendix D.

3.2.5.3 Participate in IE Briefing (Loveland, March 2005)

A briefing was held in Loveland in March 2005 with the IE and members of the Freightliner Team, including Wal★Mart, Freightliner, Battelle, the Aberdeen Test Center, and Meritor WABCO. The status of the project was reviewed, including review of tractor and trailer instrumentation, data management process implementation, and fleet support development. At that time, the IE was given a tour of the fleet location and operations. Because this briefing was an on-site activity, no formal presentation slides were prepared.

3.2.5.4 Place Trailers in Service

Trailers were placed in service as they were completed and inspected by Wal★Mart according to their standard preparation activities for service. As appropriate, the Wal★Mart fleet managers pointed out items needing adjustment. Wal★Mart also designed signs to be placed at the nose and rear of the trailers. The signs, shown in Figure 3-26 below, were intended to facilitate trailer assignments and dispatching, hence reducing the risk of FOT trailers leaving the Loveland service area.

Figure 3-26. Trailer Decals Implemented by Wal★Mart to Facilitate Trailer Assignments, Dispatch and Tracking: Outside the Trailer (left), Inside the Trailer (bottom right) and Decal Close-up (top right)

3.2.6 Data Management Plan Development

In parallel with the preparation of the vehicles for data collection, the Freightliner Team refined and implemented the data management plan as defined in the proposal (Freightliner 2005). As such, the Freightliner Team developed and implemented the infrastructure and processes needed for data collection and management, including transferring, validating, and storing the data collected. This section provides details on these activities, specifically data collection, data harvesting, data processing, and data management for each type of data collected: onboard driving data (Section 3.2.6.1), fleet maintenance data (Section 3.2.6.2), survey data (Section 3.2.6.3) as well as operational data (Section 3.2.6.4).

3.2.6.1 Onboard Driving Data

Data Description

Tables 3-9 through 3-12 list the specific data collected, including engineering units, source, and sampling rates for the tractors and trailers in Template 2, Template 3, and the "driver baselining" of existing Wal★Mart tractors. For a complete description of the channels that were collected on the existing Wal★Mart tractors during Phase 0 "driver baselining" of Template 3, see Appendix C.

Depending on the vehicle type, the DAS received data from several sources, using standard vehicle data buses (SAE J1939 and SAE J1587), technology-specific buses (ECBS or radar technology data buses), GPS receivers, and analog sensors (accelerometers, yaw rate sensors). Provided that "the tractor ignition is on" and "parking brake is off," the data were acquired continuously at a fixed sampling rate of 10 Hz and stored in segmented time history files on the onboard storage media. A time history file contained metadata information and up to 10 minutes of driving data sampled at 10 Hz. Less than 10 minutes of data were collected when the tractor/trailers started and stopped on a minute which was not a multiple of 10 (0, 10, 20, etc.). In instances where the transmission rate of the bus data was lower than 10 Hz, data were still stored in the files at 10 Hz.

Non-continuous triggered events were collected only for video data. The Freightliner Team collected video data with a forward-facing video camera and a separate DAS unit on the Template 3 ECBS tractors to supplement the onboard driving data collected, and assist with the validation of vehicle dynamics engineering calculations. The supplemental DAS unit (video DAS) was an embedded computer system developed by the Aberdeen Test Center to record still photo snapshots and video movie clips on removable solid-state media when prompted by the primary onboard driving data DAS. With a video DAS recording rate of 6.5 Mb/minute, a 512-Mb flash card could store 78 minutes of video. Although the video camera was always active, criteria were defined in cooperation with the IE to trigger video data capture in critical safety maneuvers, hence avoiding the unnecessary capture of routine driving maneuvers.

Table 3-8 is a list of the triggers developed by the Freightliner Team and the IE. A 0.5-second moving average was applied to all parameters except ABS activation.

Table 3-8. Video Triggering Events

Trigger #	Trigger Description
1	Time To Collision < 1 second and Speed > 20 mph
2	Brake Pressure > 50 psi
3	Steering Angle > 120 degrees and Speed > 20 mph
4	Longitudinal Acceleration < -0.31 g and Brake Pedal Position > 0%
5	Lateral Acceleration > 0.35 g and Speed > 20 mph
6	ABS activation
7	Brake Pedal Position > 70% and Speed > 20 mph
8	Speed difference between adjacent wheels > 7 ft/s and Speed > 20 mph
9	Yaw Rate > 30 degrees/sec and Speed > 20 mph

Fault code information was recorded in the time history files as well as in separate files. The intent was to store fault code information only when a fault code was generated, hence reducing the overall size of the data files created. Unfortunately, the programming of these files and subsequent decoding did not yield usable or meaningful results.

Further details on the data elements collected in the files are included in Appendix C. Information on the specific addresses used to capture data from the vehicle data bus and arithmetic manipulations of the data to generate engineering data from digital encoded data are all detailed in Appendix C.

Table 3-9. Onboard Data Collected from the Template 2 Tractors

Name	Units	Source	Metadata	Sample Rate
DAS ID	n/a	DAS	x	
VIN	n/a	Vehicle Data Bus	x	
Relative Time	seconds	DAS		10 Hz
GPS Data				
GPS Time	HH:MM:SS	Analog Sensor (GPS)	x	1 Hz
GPS Speed	Knots	Analog Sensor (GPS)	x	
GPS Heading	deg	Analog Sensor (GPS)	x	
GPS Latitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Longitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Altitude	meters	Analog Sensor (GPS)		1 Hz
Vehicle Data				
Ambient Air Temperature	degF	Vehicle Data Bus	x	
Odometer	miles	Vehicle Data Bus	x	
Vehicle Speed	ft/s	Vehicle Data Bus		10 Hz
CC Switch Status	n/a	Vehicle Data Bus		5 Hz
Throttle Position	%	Vehicle Data Bus		10 Hz
Engine Speed	rpm	Vehicle Data Bus		10 Hz
Engine Load	%	Vehicle Data Bus		10 Hz
Wheel speed – roadside steer	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside steer	ft/s	Analog Sensor		10 Hz
Wheel speed – roadside drive 1	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside drive 1	ft/s	Analog Sensor		10 Hz
Wheel speed – roadside drive 2	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside drive 2	ft/s	Analog Sensor		10 Hz
Suspension Airbag Pressure	psi	Analog Sensor		10 Hz
Steering Angle	deg	Analog Sensor/Bus		10 Hz
Windshield Wiper Activation	n/a	Digital I/O		10 Hz
Headlights	n/a	Digital I/O		10 Hz
Turn Signals	n/a	Digital I/O		10 Hz
Vehicle Fault Codes (Active DTC)	n/a	Vehicle Data Bus		10 Hz
Accelerometer Data				
Longitudinal Acceleration	g	Analog Sensor (DAS)		10 Hz
Lateral Acceleration	g	Analog Sensor (DAS)		10 Hz
Yaw Rate	deg/s	Analog Sensor (DAS)		10 Hz
Brake System Data				
Control Air Pressure (TCV)	psi	Analog Sensor		10 Hz
Brake Pedal Percentage	%	Analog Sensor / Bus		10 Hz
Chamber Pressure – roadside steer	psi	Analog Sensor		10 Hz
Chamber Pressure – curbside steer	psi	Analog Sensor		10 Hz
Chamber Pressure - roadside drive 1	psi	Analog Sensor		10 Hz
Chamber Pressure - curbside drive 1	psi	Analog Sensor		10 Hz
Chamber Pressure - roadside drive 2	psi	Analog Sensor		10 Hz
Chamber Pressure - curbside drive 2	psi	Analog Sensor		10 Hz
Compressor Governor Signal	psi	Analog Sensor		10 Hz
Forward Radar / ACC Data				
Target Range	ft	Radar Data Bus		10 Hz
Forward Vehicle Speed	ft/s	Radar Data Bus		10 Hz
Target Azimuth (Object angle)	deg	Radar Data Bus		10 Hz
Target Detect	n/a	Radar Data Bus		10 Hz
ACC Alert Signal	n/a	Radar Data Bus		10 Hz

Table 3-10. Onboard Data Collected from the Template 2 Trailers

Name	Units	Source	Metadata	Sample Rate
DAS ID	n/a	DAS	x	
Relative Time	seconds	DAS		10 Hz
GPS Data				
GPS Time	HH:MM:SS	Analog Sensor (GPS)	x	1 Hz
GPS Speed	Knots	Analog Sensor (GPS)	x	
GPS Heading	deg	Analog Sensor (GPS)	x	
GPS Latitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Longitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Altitude	meters	Analog Sensor (GPS)		1 Hz
Vehicle Data				
Suspension Airbag Pressure	psi	Analog Sensor		10 Hz
Wheel speed, roadside front	ft/s	Analog Sensor		10 Hz
Wheel speed, roadside rear	ft/s	Analog Sensor		10 Hz
Wheel speed, curbside front	ft/s	Analog Sensor		10 Hz
Wheel speed, curbside rear	ft/s	Analog Sensor		10 Hz
Accelerometer Data				
Longitudinal Acceleration	g	Analog Sensor (DAS)		10 Hz
Lateral Acceleration	g	Analog Sensor (DAS)		10 Hz
Yaw Rate	deg/s	Analog Sensor (DAS)		10 Hz
Brake System Data				
Chamber Pressure, roadside front	psi	Analog Sensor		10 Hz
Chamber Pressure, roadside rear	psi	Analog Sensor		10 Hz
Chamber Pressure, curbside front	psi	Analog Sensor		10 Hz
Chamber Pressure, curbside rear	psi	Analog Sensor		10 Hz

Table 3-11. Data Collected on Driver Profiling Tractors during Template 3 Baseline Phase

Name	Units	Source	Metadata	Sample Rate
DAS ID	n/a	DAS	x	
VIN	n/a	Vehicle Data Bus	x	
Relative Time	seconds	DAS		10 Hz
GPS Data				
GPS Time	HH:MM:SS	Analog Sensor (GPS)	x	1 Hz
GPS Speed	Knots	Analog Sensor (GPS)	x	1 Hz
GPS Heading	deg	Analog Sensor (GPS)	x	1 Hz
GPS Latitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Longitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Altitude	meters	Analog Sensor (GPS)		1 Hz
Vehicle Data				
Ambient Air Temperature	degF	Vehicle Data Bus	x	0.1 Hz
Odometer	miles	Vehicle Data Bus	x	
Vehicle Speed	ft/s	Vehicle Data Bus		10 Hz
CC Switch Status	n/a	Vehicle Data Bus		5 Hz
Throttle Position	%	Vehicle Data Bus		10 Hz
Engine Speed	rpm	Vehicle Data Bus		10 Hz
Engine Torque	N-m	Vehicle Data Bus		1 Hz
Engine Load	%	Vehicle Data Bus		10 Hz
Engine Brake Activation (status)	n/a	Vehicle Data Bus		5 Hz
Engine Brake Activation (percent)	%	Vehicle Data Bus		1 Hz
Brake System Data				
Brake Activation	n/a	Vehicle Data Bus		1 Hz
ABS Control Information	n/a	Vehicle Data Bus		10 Hz
Park Brake Status	n/a	Vehicle Data Bus		1 Hz
Accelerometer Data				
Longitudinal Acceleration	g	Analog Sensor (DAS)		10 Hz
Lateral Acceleration	g	Analog Sensor (DAS)		10 Hz
Yaw Rate	deg/s	Analog Sensor (DAS)		10 Hz
Forward Radar / ACC Data				
Target Range	ft	Radar Data Bus		10 Hz
Forward Vehicle Speed	ft/s	Radar Data Bus		10 Hz
Target Azimuth (Object angle)	deg	Radar Data Bus		10 Hz
Target Detect	n/a	Radar Data Bus		10 Hz
ACC Mode/Alerts	n/a	Radar Data Bus		10 Hz

Table 3-12. Onboard Data Collected from the Template 3 Tractors

Name	Units	Source	Metadata	Rate
DAS ID	n/a	DAS	x	
VIN	n/a	Vehicle Data Bus	x	
Relative Time	seconds	DAS		10 Hz
GPS Data				
GPS Time	HH:MM:SS	Analog Sensor (GPS)	x	1 Hz
GPS Speed	Knots	Analog Sensor (GPS)	x	
GPS Heading	deg	Analog Sensor (GPS)	x	
GPS Latitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Longitude	deg	Analog Sensor (GPS)	x	1 Hz
GPS Altitude	meters	Analog Sensor (GPS)		1 Hz
Vehicle Data				
Ambient Air Temperature	degF	Vehicle Data Bus	x	0.1 Hz
Odometer	miles	Vehicle Data Bus	x	
Vehicle Speed	ft/s	Vehicle Data Bus		10 Hz
CC Switch Status	n/a	Vehicle Data Bus		5 Hz
Throttle Position	%	Vehicle Data Bus		10 Hz
Engine Speed	rpm	Vehicle Data Bus		10 Hz
Engine Load	%	Vehicle Data Bus		10 Hz
Wheel speed – roadside steer	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside steer	ft/s	Analog Sensor		10 Hz
Wheel speed – roadside drive 1	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside drive 1	ft/s	Analog Sensor		10 Hz
Wheel speed – roadside drive 2	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside drive 2	ft/s	Analog Sensor		10 Hz
Suspension Airbag Pressure	psi	Analog Sensor		10 Hz
Steering Angle	deg	Analog Sensor/Bus		10 Hz
Windshield Viper Activation	n/a	Digital I/O		10 Hz
Headlights	n/a	Digital I/O		10 Hz
Turn Signals	n/a	Digital I/O		10 Hz
Accelerometer Data				
Longitudinal Acceleration	g	Analog Sensor (DAS)		10 Hz
Lateral Acceleration	g	Analog Sensor (DAS)		10 Hz
Yaw Rate	deg/s	Analog Sensor (DAS)		10 Hz
Brake System Data				
Brake Activation	n/a	Vehicle Data Bus		1 Hz
Control Air Pressure (TCV)	psi	Analog Sensor		10 Hz
Brake Pedal Percentage	%	Analog Sensor / Bus		10 Hz
Vehicle Brake Control Information	n/a	Vehicle Data Bus		10 Hz
Chamber Pressure – roadside steer	psi	Analog Sensor		10 Hz
Chamber Pressure – curbside steer	psi	Analog Sensor		10 Hz
Chamber Pressure – roadside drive 1	psi	Analog Sensor		10 Hz
Chamber Pressure – curbside drive 1	psi	Analog Sensor		10 Hz
Chamber Pressure – roadside drive 2	psi	Analog Sensor		10 Hz
Chamber Pressure – curbside drive 2	psi	Analog Sensor		10 Hz
Compressor Governor Signal	psi	Analog Sensor		10 Hz
Forward Radar / ACC Data				
Target Range	ft	Radar Data Bus		10 Hz
Forward Vehicle Speed	ft/s	Radar Data Bus		10 Hz
Target Azimuth (Object angle)	deg	Radar Data Bus		10 Hz
Target Detect	n/a	Radar Data Bus		10 Hz
ACC Audio Warning	n/a	Radar Data Bus		10 Hz
Video Data				

Continued: Trailer data collected onboard the Template 3 tractor DAS

Table 3-12 (continued). Onboard Data Collected from the Template 3 Tractors

Trailer Data (Collected onboard T3 tractor DAS unit)				
Name	**Units**	**Source**	**Metadata**	**Sample Rate**
Chamber Pressure – roadside 1	psi	Analog Sensor		10 Hz
Chamber Pressure – curbside 1	psi	Analog Sensor		10 Hz
Chamber Pressure - roadside 2	psi	Analog Sensor		10 Hz
Chamber Pressure - curbside 2	psi	Analog Sensor		10 Hz
Suspension Airbag Pressure	psi	Analog Sensor		10 Hz
Wheel speed – roadside 1	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside 1	ft/s	Analog Sensor		10 Hz
Wheel speed – roadside 2	ft/s	Analog Sensor		10 Hz
Wheel speed – curbside 2	ft/s	Analog Sensor		10 Hz
Longitudinal Acceleration	g	Analog Sensor (DAS)		10 Hz
Lateral Acceleration	g	Analog Sensor (DAS)		10 Hz
Yaw Rate	deg/s	Analog Sensor (DAS)		10 Hz

Data Transfer, Processing, and Storage

This section describes the data management processes developed and implemented by the Freightliner Team once the driving data had been collected onboard the vehicles.

Figure 3-27 shows the process for the driving data collection, transfer, and storage, from the collection point (vehicle), through Battelle for data validation, and to the final delivery point, the IE, for analysis.

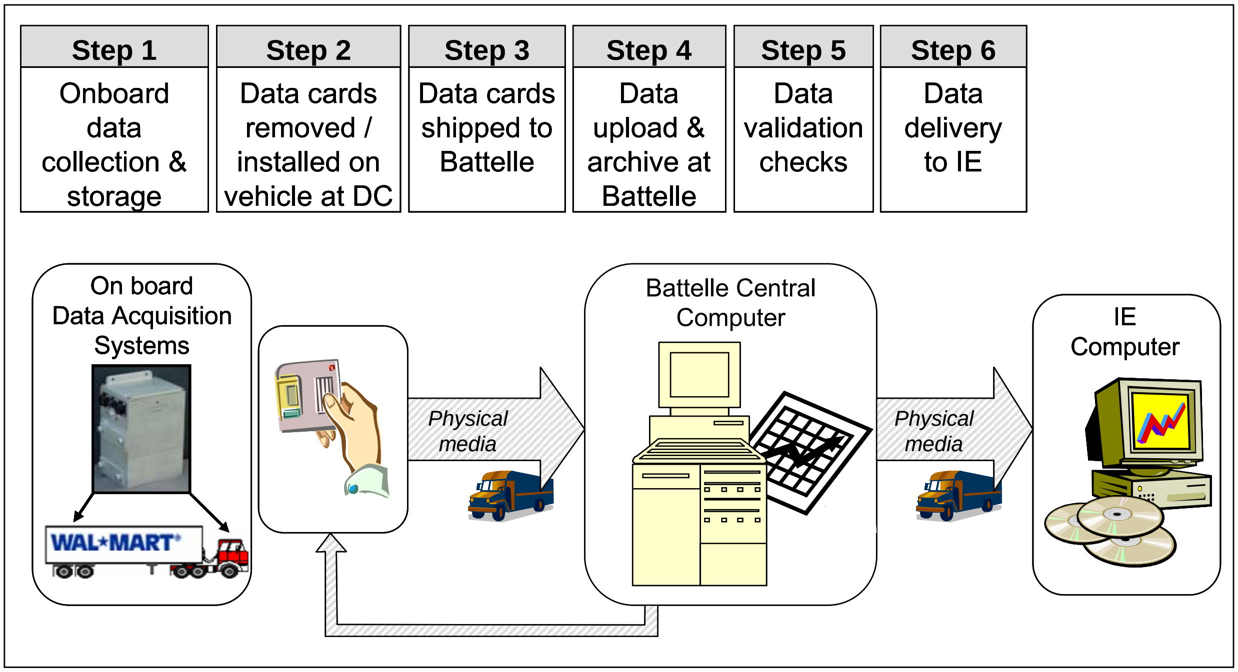


Figure 3-27. ECBS FOT Step-By-Step Data Collection and Management Process for Onboard Data

Step 1 – Onboard Data Collection and Storage

The onboard storage media used in the full DAS units were large-capacity, removable solid-state storage devices, 1-GB Personal Computer Memory Card International Association (PCMCIA) cards, sized sufficiently to store data collected for over 14 days on tractors and up to several months on trailers. The data were stored in the form of multiple blob (binary large object[5]) files, each containing up to 10 minutes of onboard driving data.

Step 2 – Data Download from the Vehicle

The original plan to use a wireless network to upload data at the terminal was not permissible, because it would have conflicted with the wireless network already in place at the terminal for Wal★Mart daily operations. As such, the Freightliner Team rethought its original plan and utilized periodic manual transfer of data cards. The data collected were manually transferred at the Wal★Mart terminal by trained, designated individuals who removed and replaced the data-

[5] Binary Large Object refers to a variable or file in which a large block of data of non-universal/standard structure is stored. Usually only the system that creates the file knows the definition of the structure used to interpret the data contained.

loaded PCMCIA cards from the DAS units with new, empty cards. More than 300 1-GB PCMCIA cards were uniquely labeled and provided to the fleet. Upon removing and replacing PCMCIA card, the trained individuals noted the card number, date of removal/installation, and vehicle number on a tracking sheet provided by the Freightliner Team (Figure 3-28). Periodically, a copy of the tracking sheet was sent to Battelle. Data cards were removed as frequently as possible within the Wal★Mart fleet operational constraints: theoretically on a weekly basis for the tractors whose drivers returned to the terminal for their assigned day off, and on a monthly basis for trailers.

Step 3 – Data Cards Transfer to Battelle

The data cards removed from the vehicles were shipped to Battelle (Columbus, Ohio) on a weekly basis using pre-labeled FedEx envelopes.

The bulk of the data processing activities took place during the following steps (4 – 5).

Step 4 – Data Upload to the Central Computer

In this step, the data were uploaded from the data cards to the Battelle central computer, or server, for further processing and archiving. The uploaded data were in the form of multiple blob files, each containing (up to) 10 minutes worth of onboard driving data. Blob files were named with a unique ID that included the time and date in which the data included in the file were collected, as well as an identifier for the DAS collecting the data. Data were stored in the database in the compressed blob format for space considerations. Using the tracking sheet completed by the Wal★Mart staff, Battelle also captured data card numbers and dates of installation and removal. Also, the total capacity of the data cards was retrieved during upload of the data into the server. Upon successful upload of the data, the data cards were reformatted and shipped back to the Wal★Mart fleet for re-use.

			MONTH OF OCTOBER							
			Week 1 10/3 to 10/9		Week 2 10/10 to 10/16		Week 3 10/17 to 10/23		Week 4 10/24 to 10/30	
	Previous Card	Installed Date	Date	Card	Date	Card FOT	Date	Card FOT	Date	Card FOT
	FOT-0123	24-Sep								
	FOT-0009	25-Sep								
	FOT-0242	24-Sep	10/5	FOT-0185						
	FOT-0271	10-Sep								
	FOT-0227	23-Sep								
	Utah									
	FOT-0255	24-Sep								
	FOT-0040	23-Sep								
	FOT-0219	9-Sep								
	FOT-0296	10-Sep	10/8	FOT-0262						
	FOT-0320	1-Aug								
	FOT-0004	23-Sep								
	FOT-0233	24-Sep								
	FOT-0253	24-Sep	10/9	FOT-0220						
	FOT-0258	24-Sep								
	FOT-0289	?	10/3	?						
	FOT-0152	28-Aug	10/7	FOT-0322						
Trac-tor IDs	FOT-0303	23-Sep								
	FOT-0259	23-Sep								
	FOT-0307	23-Sep								
	FOT-0180	6-Sep								
	FOT-0173	23-Sep	10/9	FOT-0257						
	FOT-0133	25-Sep	10/8	FOT-0167						
	FOT-0065	6-Sep								
	FOT-0298	6-Sep								
	FOT-0305	9-Sep								
	FOT-0177	23-Sep								
	FOT-0282	??	10/6	FOT-0214						
	FOT-0125	28-Aug	10/8	FOT-0204						
	FOT-0168	24-Sep								
	FOT-0142	27-Aug	10/7	FOT-0110						
	n/a		10/7	FOT-0277						
	FOT-0203	24-Sep								
	FOT-0186	24-Sep								
	FOT-0029	24-Sep	10/9	FOT-0193						
	FOT-0191	24-Sep								
	n/a		10/5	FOT-0020						
	FOT-0321	23-Sep								
	FOT-0264	24-Sep	10/8	-0215/-0129						
	FOT-0224	24-Sep	10/8	FOT-0129						
	FOT-0194	25-Sep								
	FOT-0033	25-Sep								
	FOT-0013	23-Sep								
	n/a		10/?	FOT-0???						
	FOT-0159	23-Sep								
	FOT-0278	23-Sep								
	FOT-0275	25-Sep	10/5	FOT-0032						
	FOT-0174	6-Sep	10/5	FOT-0324						
	FOT-0016	23-Sep								
	FOT-0297	11-Sep								
	FOT-0212	23-Sep								
	FOT-0248	23-Sep								
	FOT-0118	24-Sep								
	FOT-0176	28-Aug								
	FOT-0286	23-Sep	10/9	FOT-0299						

Figure 3-28. Card Tracking Sheet used in the Field by Wal★Mart

Step 5 – Data Processing, Validation, and Archival

Upon loading the data to the Battelle server, data processing routines were conducted to check for validity and accuracy of the data, and to generate summary statistics and supporting tables for the IE. The section below details the data processing activities and data management processes.

Blob files were processed weekly upon upload at Battelle in order to provide quick feedback to the Freightliner Team on any problems identified in the onboard driving data or in the collecting sensors. The result of the processing was a database that was used by Battelle for FOT summarization, reporting, and for providing validation information and summary statistics to the IE. Five steps were required for processing the blob files at Battelle:

1. Decompression and conversion of blob files to engineering units files (using a data parser)
2. Validation of data by both channel bound screening and cross-channel consistency checking
3. Calculation of summary statistics from driving data for storage in analysis database
4. Matching of tractor-trailer blob files (T2)
5. Archive of blob files for permanent storage at Battelle and delivery to IE.

Decompression and Conversion of Blob Files

Battelle developed a parsing program that decompresses and converts blob files to a comma separated value (CSV) file in which the channels are transformed to engineering units. The new parsing program, based on the parser originally developed by Aberdeen Test Center, was improved to meet the needs and requirements of the FOT, in particular to handle the large number of files collected by the many vehicles on the road.

Once the blob files had been decompressed and converted to CSV files, Battelle utilized the decompressed and converted files to perform validation and calculate summary statistics for the Battelle analysis database. Decompressed blob files were not stored in the analysis database due to storage space considerations; blobs were stored in their raw format.

Validations

The following data quality checks were performed for each blob file:

1. Start date and time was provided for each blob as header information associated with the time history data. Start and stop times were compared with spatially adjacent blobs. Start and stop time were also compared with the minimum and maximum times contained within the blob.

2. The VIN in the blob metadata was looked up to ensure that the data could be assigned to a specific FOT vehicle.
3. The length of each blob was checked to ensure that the data did not repeat internally.
4. Each channel was screened to ensure that its values were within a reasonable range for the type of data reported.
5. Odometer readings were checked between blobs for consistency. When odometer values were missing, GPS coordinates and spatially adjacent blob values were used to impute missing values.
6. GPS coordinates were imputed if missing when no distance was traveled.
7. Target range, range rate, and azimuth were checked with the Target Detect Alerts to ensure that a target was present.

Note that the objective of these checks was to verify that data were being collected reliably, were within expected bounds, and were internally consistent. Due to data processing considerations, these were not checks on the precision of the data, as transducer calibration data were maintained separately.

The results of blob file data validation were stored in the Battelle analysis database. Only the relevant subset of validations was performed on tractor and trailer data as dictated by the channels available for each template and configuration.

Summary Statistics

Statistics summarizing the driving experience of each tractor and trailer were calculated for each blob. Data summaries included the following small subset of summaries:

1. VMT
2. Average, maximum, and minimum road speed
3. Counts of ABS and ECBS activations, CWS alerts, and ACC audio warnings
4. Percentage of time the cruise control was active
5. Maximum brake pedal percentage and maximum range rate
6. Maximum and minimum target azimuth, analog steer angle, fore/aft acceleration, lateral acceleration, and yaw rate.

Each of the listed summary statistics was stored in the Battelle analysis database for each blob file. Only the relevant subset of summary statistics was calculated on tractor and trailer data as dictated by the channels available for each template and configuration.

Structure of the Battelle Analysis Database

The following tables were created in the database, with the relationships defined by the primary and secondary data keys given in parentheses.

1. tblBlobFile (Blob File ID, Tractor Configuration ID, VIN)
2. tblBlobFile_Corrections (Blob File ID, Configuration ID, VIN)
3. tblBlobFileChannelValue (Blob File ID, Channel ID)
4. tblBlobFileError (Blob File ID, Channel ID)
5. tblTractorTrailerMatch (Blob File ID)
6. tblConfiguration (Configuration ID)
7. tblConfigurationChannel (Channel ID, Configuration ID)
8. tblVehicle (VIN)

tblBlobFile Table: The blob file table contained one record for every blob file that was received. This table served as the main source to determine which data had been received and which data had been sent to the IE. Each record contains the blob identifier, the filename, file size, processed date and time, configuration ID, DAS ID, VIN, blob start and stop time, blob start and stop odometer, blob start and stop GPS information, and a field indicating whether a blob had been sent to the IE.

tblBlobFile_Corrections Table: This table contained an entry for each blob that has corrected metadata. If metadata information was missing or zero, then the validation procedures were used to attempt to correct the information. Time, odometer, and GPS location information were all corrected when possible.

tblBlobFileChannelValue Table: The channel value table contained a minimum, maximum, and average of each value type channel, e.g., vehicle speed. For occurrence type channels such as a target detect alert, the number of occurrences and the percentage of time in an "ON" condition were recorded.

tblBlobFileError Table: The blob file error table contained a record for each validation check that failed for a blob file. Each record contained the blob identifier and an ID to indicate the validation that failed.

tblTractorTrailerMatch Table: The tractor-trailer match table contained a record for each pair of matched tractor and T2 trailer blob files. Each record contained two fields, the blob identifier of the tractor and the blob identifier of the trailer that were matched.

tblConfiguration Table: This table related the configuration file information to the configuration ID. The configuration file was loaded into the DAS. It identified the proper configuration file to be used when decoding the blob file.

tblConfigurationChannel Table: The configuration channel table contained the channel description and the valid range for that channel. Different configurations had different channel ID numbers and different validation criteria.

tblVehicle Table: The vehicle table related the tractor reference ID, the VIN, and the tractor/trailer template information.

Matching of tractor-trailer blob files (T2)

Matched data were defined as onboard driving data collected when a Template 2 tractor was pulling a Template 2 trailer. This was the only Template 2 data for which all tractor and trailer channels were collected. Other Template 2 data consisted of either tractor or trailer channels with the other channels not collected. The matching of tractor and trailer data was performed using the information from blob header files (GPS start/stop times and locations).

Matching vehicles using blob header files was computer-intensive (due to the large amount of tractor and trailer blob files); it presented the risk of erroneously matching tractor and trailer blobs due to proximity within the terminal or at a delivery site; and, in the event a trailer did not make it back to Loveland for a long time, it could be delayed, because the Freightliner Team had to wait on the trailer data to do the matching. The methodology developed by the Freightliner Team accounted for these constraints and provided the IE with the matching table.

Weekly, a procedure was run to match the trailer blobs to tractor blobs using GPS start and stop times and location data from the blob tables. The procedure first subsetted the blobs from each trailer by day and then matched them by GPS coordinates and time. The start time of the tractor and trailer blobs was required to be within 60 seconds and the latitude and longitude were required to be within 0.0002 degrees. Although the resolution of the GPS data collected was high enough to discriminate between tractor-trailers moving in close proximity, matching of tractors and trailers in the terminal area could be difficult. In most cases, Template 2 trailers were moved within the terminal by yard vehicles. They would be hooked up to FOT tractors in the terminal only upon arrival and departure from the terminal, which facilitated matching. To alleviate the problem of duplicate matches at a distribution point, tractors and trailers were not matched within 1.5 miles of the Loveland terminal and not within 5 miles of the estimated position of a Wal★Mart store. The boundary was smaller around the terminal because the position of the terminal was well known, whereas the coordinates of the Wal★Mart stores were less accurate.

<u>Archiving of Blob Files for Permanent Storage and Delivery to the IE</u>

The blob files were backed up to permanent media (digital versatile discs, or DVDs) in the delivery process. To handle the data management processes described herein, the Freightliner Team designed and implemented a server with:

- Sufficient processing power to process the harvested data in a timely manner
- Sufficient hard drive storage space to store the Battelle analysis database
- A backup system capable of backing up the Battelle analysis database and raw blob data
- Sufficient extra hard drive space and processor power to serve the Battelle analysis database data to researchers at Battelle
- Ability to burn data to DVD for delivery to the IE.

Since all the uncompressed blob files were not archived in the Battelle analysis database, storage requirements were significantly reduced.

Step 6 – Data Delivery to the IE

The Freightliner Team delivered the onboard driving data to the IE on DVDs on a monthly basis. All blob files uploaded to Battelle during the month as well as validation information, summary statistics, and matching information were supplied on the DVDs incrementally. Validation information and summary statistics were supplied in CSV files that could be appended to previous information supplied to the IE. The matching table was supplied in its entirety in CSV format each month. The Freightliner Team also sent the data parser to the IE for data processing. Upon creating DVDs, backup copies were made and stored in separate locked locations.

3.2.6.2 Maintenance Data

Whereas onboard driving data were appropriate for assessing the performance and reliability of advanced brake systems, the fleet's maintenance records were essential for assessing the maintainability and durability of the new systems. The Freightliner Team studied the Wal★Mart maintenance recording system and worked with Wal★Mart to determine the method of data transfer that would cause the least disruption, and yet provide the information needed. Since the Wal★Mart maintenance system did not have the capability of generating electronic records, processes were implemented to obtain records on paper from the work orders stored for each tractor and trailer. Wal★Mart's existing data recording and collection activities were not changed, which increased the likelihood of success in collecting complete and accurate data from the fleet.

Maintenance records, or Repair Orders (ROs), that Wal★Mart produced in its ordinary course of business for each tractor and trailer in this study were collected and delivered to the IE. As specified by the IE, the data collection efforts were focused on ROs related to brake systems and tires: The records obtained included work order information, labor hours and cost, and parts replacements and cost for all ROs related to brake systems and tires recorded on the FOT tractors and trailers from the dates at which they were placed in service to the end of the data collection period. Like most trucking companies, Wal★Mart uses the ATA coding system for its maintenance: Vehicle Maintenance Reporting System (VMRS). As such, the codes used with this data collection activity were specifically System Code 13 for braking systems and System Code 17 for tires.

The queries parameters included:

- Vehicles: All FOT tractors and all FOT trailers identification number
- Dates:
  - Phase 1 data (May 1, 2005 – October 31, 2005),
  - Phase 2 data (November 1, 2005 – April 30, 2006)
- System Codes: 13 for braking systems and 17 for tires

Once all RO reference numbers were identified, the Loveland, Colorado, Wal★Mart staff recalled the RO and printed it. The ROs include the following fields:

- Vehicle ID
- RO Number
- Date Performed
- Meter Reading
- Code 14 (Reason for Repair)
- Code 15 (Work Accomplished)
- Code 16 (Repair Priority Class)
- Code 17 (Repair Site)
- Code 18 (Technician Part Failure)
- Code 31 (System Level)
- Code 32 (Assembly Level)
- Code 33 (Component Level)
- Code 79 (Position Code)
- Part Number, Quantity, and Cost
- Labor Time (Actual)
- Labor Cost
- Comments

Once printed, ROs were then sent to Battelle. Upon receipt of the ROs, Battelle sanitized all personnel information, e.g., name and ID of the technician performing the work; and scanned the printed information into Adobe Portable Document File (PDF) format files. The sanitized PDF document containing all ROs was then sent to the IE via file transfer protocol (FTP). Maintenance data were not archived in the FOT database previously described. The schedule and protocol for acquisition of maintenance data had no effect on management of the onboard driving data. Maintenance records were collected in two batches: upon completion of Phase 1 and upon completion of Phase 2.

3.2.6.3 Survey Data

The opinions of drivers and mechanics (i.e., technicians) on performance, reliability, and maintainability of the systems under evaluation were sought by conducting surveys during the FOT. The Freightliner Team reviewed the Wal★Mart fleet operational characteristics and implemented processes to conduct the surveys taking into consideration fleet requirements, logistical issues, the FOT experimental design, and proposal (Freightliner 2005).

The plan to collect driver and technician surveys was originally developed in the proposal and refined in collaboration with the IE. Specific written surveys were developed and administered at three separate times during the project:

- Before the drivers and technicians were exposed to or trained on the new vehicles and the new technologies (i.e., before Phase 1)
- Before the drivers and technicians were exposed to the enabled technologies but after they were exposed to the FOT vehicles and brake systems (upon completion of Phase 1 but before start of Phase 2)
- After completion of Phase 2, i.e., after drivers and technicians were exposed to the FOT vehicles equipped with brake systems and enabled technologies.

This plan took advantage of the features of the experimental design of this FOT, which provided selected control periods, allowing comparisons of driver and technician responses during times when the various systems were operating and when they were not, allowing study of evolving opinions and review of the overall experience and discussions of the benefits and drawbacks of the technologies. The schedule and protocol for acquisition of survey data had no effect on management of the onboard driving data, and was developed in accordance with the experimental design and objectives of the evaluation.

The survey questions were developed by the IE and reviewed by the Freightliner Team. While surveys of drivers were developed to gain information on their perception of the system performance and their acceptance of the technology, surveys of technicians were developed to help assess the performance of the technologies, as well as their maintainability and reliability, and to identify potential strengths and weaknesses of the systems that might not be apparent to drivers and that might not emerge from the driving data. Upon review of the survey questions for each phase of the test, the Freightliner Team suggested changes to the IE, who then modified the survey questions as appropriate for their evaluation. Surveys that were submitted to the drivers and technicians are included in Appendix E.

The process for collecting survey data was as follows:

- Surveys were drafted by the IE and sent to the Freightliner Team.
- Surveys were reviewed by the Freightliner Team.
- Surveys were revised, as appropriate, by the IE.
- Surveys were printed and sent to the Wal★Mart operator by the Freightliner Team at a specified time.
- Upon receipt, Wal★Mart distributed surveys to the drivers and technicians, in mailboxes or in hand, and collected completed surveys.
- Wal★Mart sent completed surveys back to the Freightliner Team.
- A designated staff member from the Freightliner Team sanitized surveys (i.e., removed personal identifying information).
- The Freightliner Team transferred sanitized survey data to the IE, in the form of a PDF copy scan of all surveys.
- The Freightliner Team stored surveys with personal information in a designated locked location. Survey data were not archived in the FOT database previously described.

In addition to reviewing the development of survey questions, the Freightliner Team compiled and submitted appropriate documents to Battelle's U.S. Department of Health and Human Services-approved Institutional Review Board (IRB) for approval, since the opinions of drivers and mechanics who participate directly in the program were sought. Documents included the appropriate applications for exemption or approval, as well as driver and mechanic surveys. Federal Regulations require that research involving human subjects be conducted according to specific protocols to protect the rights and welfare of participants. Such research must be reviewed and approved by an independent IRB operating in accordance with Title 45, Part 46, of the Code of Federal Regulations. The approval process determines if prospective subjects provide informed consent, whether they are placed at risk, and whether such risks are outweighed by the sum of the benefits to the subject and the benefit of the knowledge gained.

All participants were asked to read an informed consent document, giving them the right to not answer the survey questions. The Freightliner Team also implemented processes to ensure that driver and mechanic identities would be protected, that the confidentiality of all responses in the survey process would be assured, and that all information resulting from surveys would be presented in aggregate form such that individual drivers or mechanics could not be identified. It was stipulated that under no circumstances will the names of participants appear in any published work resulting from this study. Driver and mechanic related information were tabulated only by confidential driver identification numbers.

3.2.6.4 Operational Data

Operational data from the fleet or the Freightliner Team members were collected to supplement the onboard, maintenance, and survey data collected. Fleet operational data collected include:

- General information on the Loveland, Colorado, stores and deliveries
- Selected dispatch information
  - Dedicated routes assigned to Template 3 drivers
  - Tractor-trailer assignments
  - Tractor routing and special assignments
- Driver assignments
- In-service dates information
- Driver / vehicle day offs
- VIN/Wal★Mart ID tables
- Trailer locations.

Freightliner Team operational data collected include:

- Vehicle ID/DAS table
- Vehicle delivery information.

These operational data were collected by the Freightliner Team through discussion and interaction with the fleet operators or with relevant Freightliner Team members. Data were either used by the Freightliner Team to generate sanitized information for the IE, or were sent directly to the IE for their analysis. Operational data records were stored either in the FOT database or in other designated locations. Data were sent to the IE generally in CSV format either with the data on DVDs (e.g., DAS-tractor-trailer assignment data) or by alternate appropriate means (email message, FTP) as necessary. The schedule and protocol for acquisition of operational data had only limited effect on management of the onboard driving data.

3.2.7 Fleet Preparation Activities

The Freightliner Team also prepared for the FOT to be conducted in the fleet operations, including developing training material for the drivers and mechanics, developing support materials and processes, and understanding driver assignments.

3.2.7.1 Development of Plan, Materials, and Procedures for Field Training of Drivers and Technicians

Training materials for drivers and for technicians were developed by the Freightliner Team. A binder summarizing all training materials as well as reference materials was generated. Figure 3-29 shows the table of contents of the training manual. Copies of the training binder were sent to the USDOT, the IE, Wal★Mart, and appropriate members of the Freightliner Team.

Visual training materials were also developed by the Freightliner Team to conduct in-class training of the drivers and technicians.

TRAINING MANUAL:
ADVANCED BRAKING TECHNOLOGIES FOR TRUCKS AND TRAILERS

Table of Contents

Tractor and Trailer Technologies	
TAB NAME	**ITEM**
Tractor/trailer **Bendix ADB**	**Bendix ADB-22X Air Disc Brakes** Bendix ADB-22X: Service Information Bendix ADB-22X: Installation guidelines - AAC steer axle Bendix ADB-22X: Installation guidelines - forward drive axle Bendix ADB-22X: Installation guidelines - rear drive axle Bendix ADB-22X: Installation Guidelines - SN N64211 Bendix Air Disc Brakes: System Description Brochure Pneumatic Disc Brake SN7 (ADB-225): Service Manual

Tractor Technologies	
TAB NAME	**ITEM**
Tractor **MW ABS**	**Meritor WABCO ABS** ABS for Trucks, Tractors & Buses Version E ECU: System Description ABS for Trucks, Tractors and Buses: Maintenance Manual ABS for Trucks, Tractors and Buses: Blink Codes ABS for Trucks, Tractors and Buses: Parts Book ABS: Installation Guide for OEM reference ABS: Installation Guide for Wheel Speed Sensor Replacement Kit ABS with ACC: Wiring and plumbing schematic ABS: Driver Tips ATC: Driver Tips
Tractor **MW ECBS**	**Meritor WABCO ECBS / ESC** Tractor ECBS / Electronic Stability Control (ESC): System Description EBS: System Description ESC Electronic Stability Control for Commercial Vehicles
Tractor **MW ACC**	**Meritor WABCO ACC** Adaptive Cruise Control (ACC): System Description Adaptive Cruise Control (ACC): Driver Display
Tractor **Bendix ABS6**	**Bendix ABS6** Bendix ABS6: Service Manual

Trailer Technologies	
TAB NAME	**ITEM**
Trailer **Arvin Meritor ADB**	
Trailer **MW Air Braking Systems**	**Meritor WABCO Air Braking Systems** In-Line Filter for trailer Air Braking Systems
Trailer **MW ABS**	**Enhanced Easy-Stop Trailer ABS with PLC** Enhanced Easy-Stop Trailer ABS with PLC: Maintenance Manual Enhanced Easy-Stop Trailer ABS with PLC: Blink Code Diagnostic Guide Enhanced Easy-Stop Trailer ABS with PLC: Parts Book Enhanced Easy-Stop Trailer ABS with PLC: Replacement kits installation guides Enhanced Easy-Stop Trailer ABS with PLC: Training Program Student Manual.pdf
Trailer **MW ECBS**	**Meritor WABCO ECBS / RSS** Trailer ECBS - System description Trailer ABS with Roll Stability Support for constant power trailers with air suspensions MW Trailer ECBS Fault Codes Trailer ECBS and Roll Stability Support (RSS) Trailer EBS with Roll Stability Support (RSS)
Trailer **Bendix ECBS**	**Bendix ECBS (TEBS4)** TEBS4 Electrical Schematic TEBS4 Power Converter Box Wiring Schematic TEBS4 Training material

Figure 3-29. Contents of the "Advanced Braking Technologies for Trucks and Trailers" Training Manual

3.2.7.2 Development of Plan, Materials, and Procedures for Field Support (Spare Parts)

Processes were developed to conduct field support of the technologies including protocols for incident reporting or notifications in case of issues in the field. A list of primary points of contact for the various technologies or instrumentation (phone tree), tracking materials, and spare parts were given to the Wal★Mart fleet. Spare parts included systems parts as well as instrumentation parts. Additional spare parts were acquired although stocked at the vendors' locations for space considerations. The vendors also provided the Wal★Mart fleet with diagnostic tools needed for the technologies installed on the vehicles.

3.2.7.3 Selection and Assignment of Drivers and Technicians

Wal★Mart assigned drivers to the vehicles per their normal assignment procedures.

In Template 3, in addition to being assigned to a new tractor, drivers were selected to drive on the dedicated routes for 6 months in Template 3. In normal Wal★Mart practices, the dedicated runs are re-competed every 6 months and different drivers may be chosen. To accommodate the need of Template 3, Wal★Mart operators committed to keeping the T3 drivers initially selected to run dedicated operations for the duration of the FOT.

3.3 Task 4: Conduct FOT

3.3.1 Chronological Description of Work Performed

Task 4 of the FOT was designed to implement the plans and associated processes or procedures to collect data for the evaluation of the technologies deployed on the Wal★Mart vehicles.

Activities were conducted to survey and train participants in the FOT, to prepare the vehicles for service, and to conduct final inspection. The IE was also invited to observe activities taking place at the Loveland terminal and to learn about Wal★Mart operations. The official start day of the tractor was defined as the day when a final checkout was conducted on a given FOT vehicle at the Loveland facility. Data collected prior to the checkout date were stored in a separate database labeled pre-FOT data.

As the data collection period of the FOT was officially launched on May 1, 2005, processes described earlier for data collection and data management were implemented and any issues raised in the field were promptly addressed. On June 9, 2005, the Freightliner Team presented the status of the project in a briefing conducted at the USDOT.

At the end of the first phase of data collection in October, the Freightliner Team prepared for the activation of the enabled safety technologies and the start of Phase 2 data collection. Drivers and technicians were surveyed and trained on the enabled technologies prior to the activation of the technologies on their assigned tractors. Maintenance data were collected for the first phase of the FOT data collection. Processes for data collection and management implemented for Phase 1 remained in place, and issues raised in the field were promptly addressed.

As Phase 2 data collection ended on April 30, 2005, drivers and technicians were surveyed a final time and the instrumentation was removed from the vehicles. Maintenance records were obtained and brake systems were inspected.

3.3.2 Final Preparation Before Onboard Data Collection

3.3.2.1 Conduct Field Training: Drivers and Mechanics

Driver and technician training was conducted by the Freightliner Team upon the start of the data collection period. Copies of the materials developed during Tasks 2 & 3 were provided to the Wal★Mart fleet as reference materials.

Multiple training sessions were held at the Loveland terminal with drivers, technicians and operators between March 8 and March 16, 2006. Training was conducted by representatives of Meritor WABCO, Bendix, and GE TIP. Figure 3-30 illustrates the training schedule conducted on March 8 through 12, 2005, by Meritor WABCO and GE TIP. A similar schedule was implemented for the technician training sessions conducted by Bendix representatives a week later. Classroom as well as hands-on training was conducted as appropriate. The IE witnessed training activities on March 9, 2005.

	Tuesday 8-Mar	Wednesday 9-Mar	Thursday 10-Mar	Friday 11-Mar	Saturday 12-Mar
AM	**Driver Training** Drivers Ops Managers Managers **Technicians Training** Week Shift 1 First group *(1st group working)*	**Technicians Training** Week Shift 1 First group (cont) **Technicians Training** Week Shift 1 Second group	**Technicians Training** Week Shift 1 Second group (cont)	**Technicians Training** WE Shift 1 First group	**Technicians Training** WE Shift 1 Second group
Afternoon (>4pm)	**Technicians Training** Week Shift 2 First group *(2nd group working)*	**Technicians Training** Week Shift 2 Second group + Midnight shift	GE Training	**Technicians Training** WE Shift 2 First group **Technicians Training** WE Shift 2 Second group	

Figure 3-30. Schedule of the March 8 – 12, 2005 Training of Drivers, Technicians, and Operators by Meritor WABCO and GE Tip

3.3.2.2 Collect Driver and Mechanic Surveys Prior to the FOT

At the time the drivers and technicians were gathered for training, the first set of surveys was conducted and completed. Any supplemental surveys for drivers not attending the formal training sessions were completed subsequently.

3.3.2.3 Preparation of FOT Tractors and Trailers by Wal★Mart

Prior to placing any new vehicle in service, Wal★Mart conducts pre-defined preparation activities: installation of Qualcomm antennas on tractors, inspections of vehicle systems, and installation of special decals. Wal★Mart drivers also prepare their vehicles by installing additional radios or personal commodity equipment (e.g., thermometers, extra mattresses, microwaves). These activities are standard processes of the Wal★Mart fleet. Such activities took place on the FOT tractors, and had no effect on the conduct or outcomes of the test.

3.3.2.4 Final Preparation and Validation of the FOT Vehicles

In parallel to Wal★Mart preparation of the vehicles for service, the Freightliner Team conducted final checkout of the FOT vehicles. As such, any changes that were made to the vehicles after delivery to the fleet were reviewed. Changes included instrumentation changes such as replacement of a broken transducer, reprogramming of the DAS software, and vehicle changes such as repositioning of the brake chamber inlet and outlet valves on selected trailers. None of the changes made to the vehicle systems were out of the ordinary.

The Freightliner Team conducted the final vehicle validation checkout in April 2005, during which a qualified QC engineer inspected each tractor in the field and recorded information such as DAS ID, DAS configuration file version, DAS firmware version, data card number, and vehicle mileage. Detailed instructions of the checkout activities conducted before the start of the FOT data collection are included in Appendix D.

3.3.2.5 Final Data Harvesting, Collection, and Transfer Checkout

The Freightliner Team continued to refine and implement processes needed for data collection and transfer. For example, Wal★Mart staff was trained on the processes developed for data card removal, replacement, tracking, and shipping.

3.3.2.6 USDOT Mid-project Briefing & Video

As the data collection started for the FOT, as described in the following section, a mid-project briefing was organized at the USDOT in Washington DC on June 9, 2005 with the USDOT, the IE, and members of the Freightliner Team, namely Freightliner and Battelle. Work conducted in Tasks 1 through 3 was presented and the first video deliverable, also documenting the work conducted in Tasks 1 through 3, was shown to all attendees. One of the two pilot tractors built to Wal★Mart specifications and equipped with the technologies under evaluation in this FOT was also displayed on the sidewalk near the USDOT. All attendees were given the opportunity to view the technologies integrated on the tractor as well as the instrumentation. The IE also presented the status of their activities. Briefing support slides were submitted to the USDOT after the meeting.

3.3.3 Data Collection

Data collection, transfer, validation, and management as deployed during Task 4 are discussed in this section. Associated activities related to fleet, technology, and instrumentation support are also described as appropriate.

3.3.3.1 Phase 0 Data Collection (Template 3)

Data described in earlier sections were first collected from October 17, 2004, to February 23, 2005, on the eight International tractors driven by the drivers selected by the Wal★Mart fleet for the dedicated Template 3 routes. All drivers but one of the baseline drivers were, as originally planned, assigned to the Template 3 tractors. The change was dictated by the operational needs of the Wal★Mart fleet. Sanitized driver assignment data were provided to the IE for their analyses.

Table 3-13 lists the vehicle miles collected for each tractor during the Template 3 baseline phase.

Table 3-13. Summary Data Collected on Baseline Template 3 Tractors

Vehicle ID	Start Date	Finish Date	Data Miles Collected
T3B-01	10/18/2004	2/23/2005	28,315
T3B-02	10/18/2004	10/24/2004	1,429
T3B-03	10/17/2004	2/2/2005	22,305
T3B-04	10/17/2004	12/13/2004	9,149
T3B-05	10/17/2004	11/6/2004	6,972
T3B-06	10/18/2004	2/15/2005	28,672
T3B-07	10/17/2004	2/20/2005	29,547
T3B-08	10/19/2004	12/31/2004	18,455
Overall	10/17/2004	2/23/2005	144,844

Data from the baseline phase of Template 3 were processed, validated, and stored in the database. The Freightliner Team sent the data to the IE in four installments as follows:

- January 5, 2005 (1 DVD)
- January 24, 2005 (updated first installment)
- February 14, 2005 (3 DVDs)
- March 17, 2005 (1 DVD).

Upon completion of the baseline data collection, instrumentation was removed from the International tractors by the Aberdeen Test Center and recycled, as appropriate, for use on the FOT vehicles or for use as spare components.

3.3.3.2 Phase 1 Onboard Data Collection

Collection of onboard data was officially launched on May 1, 2005. The Freightliner Team utilized all processes described earlier to collect, upload, store, validate, and transfer the onboard data to the IE. In parallel to onboard data collection, maintenance and survey data were also collected.

As needed, issues that were raised in the field were addressed and resolved. Challenges included interferences on the driver's CB radio caused by the DAS on some tractors. Drivers own their CB radios, and model/makes vary widely. It was found in the field that on some tractors, the power supply used by the Aberdeen Test Center in the DAS interfered with the ability of the CB radios to transmit and receive. Extensive efforts by all members of the Freightliner Team failed to identify any clear, single source of interference beyond the power supply of the DAS. Consequently, custom solutions were designed for and implemented on each affected tractor. Fixes implemented included a combination of one or more of the following: insulating material between the DAS unit and its mounting plate, conductive lead connecting the DAS to the vehicle ground, alternate power supply, and installing higher-end CB radios. While fixes were being implemented on each tractor, some data were lost due to the removal of the DAS power fuse by dissatisfied drivers, despite the assistance of the Wal★Mart fleet operators, who urged drivers not to do so.

Throughout the collection of onboard data, the Freightliner Team worked closely with Wal★Mart staff to encourage the timely removal of data cards from the vehicles, hence limiting the loss of data that occurs once the data card has reached its full capacity. The Freightliner Team used data card tracking sheets completed in the field and data stored in the FOT database to visually track the status of the data collection from a card usage standpoint. Figures 3-31 and 3-32 illustrate the data card tracking information compiled by the Freightliner Team, showing for each tractor and each day the status of the onboard data collection according to the data cards collected.

Other issues were raised as the vehicles and systems were deployed in the field. For example, after some drivers requested a slight adjustment in the ECBS brake pedal return, Freightliner and Meritor WABCO implemented a design change on these vehicles. Another issue of concern was evidence of failures of the steering angle sensor embedded in the steering wheel assembly on ECBS tractors. Freightliner and Meritor WABCO studied the source of the problem, and readily implemented appropriate changes. Such modifications are not unusual when novel systems are implemented on vehicles, and fixes are typically worked out among the OEM, its vendors, and the fleet.

As data were uploaded, validated, and stored on the Battelle server, the Freightliner Team generated data summaries that were sent to the USDOT and the IE. Data summaries (example shown in Figure 3-33) were developed in collaboration with the USDOT and the IE to provide the team with a snapshot of the status of the data collection as the field test progressed. Results as well as field issues were discussed at weekly conference calls with the Freightliner Team, the USDOT, and the IE.

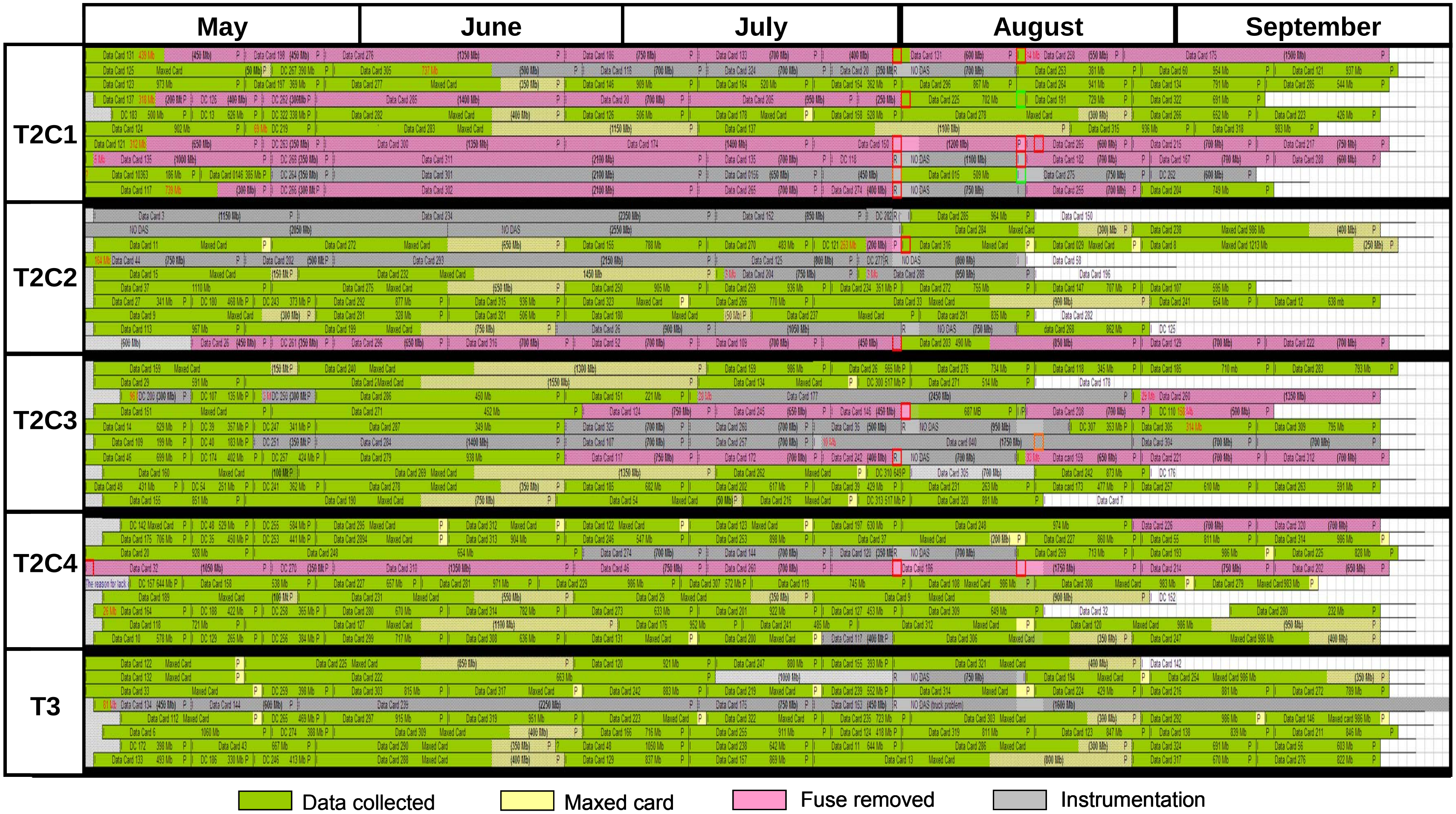


Figure 3-31. Visual Representation of the Data Collection Status using Data Card Information for Each Tractor as a Function of Time

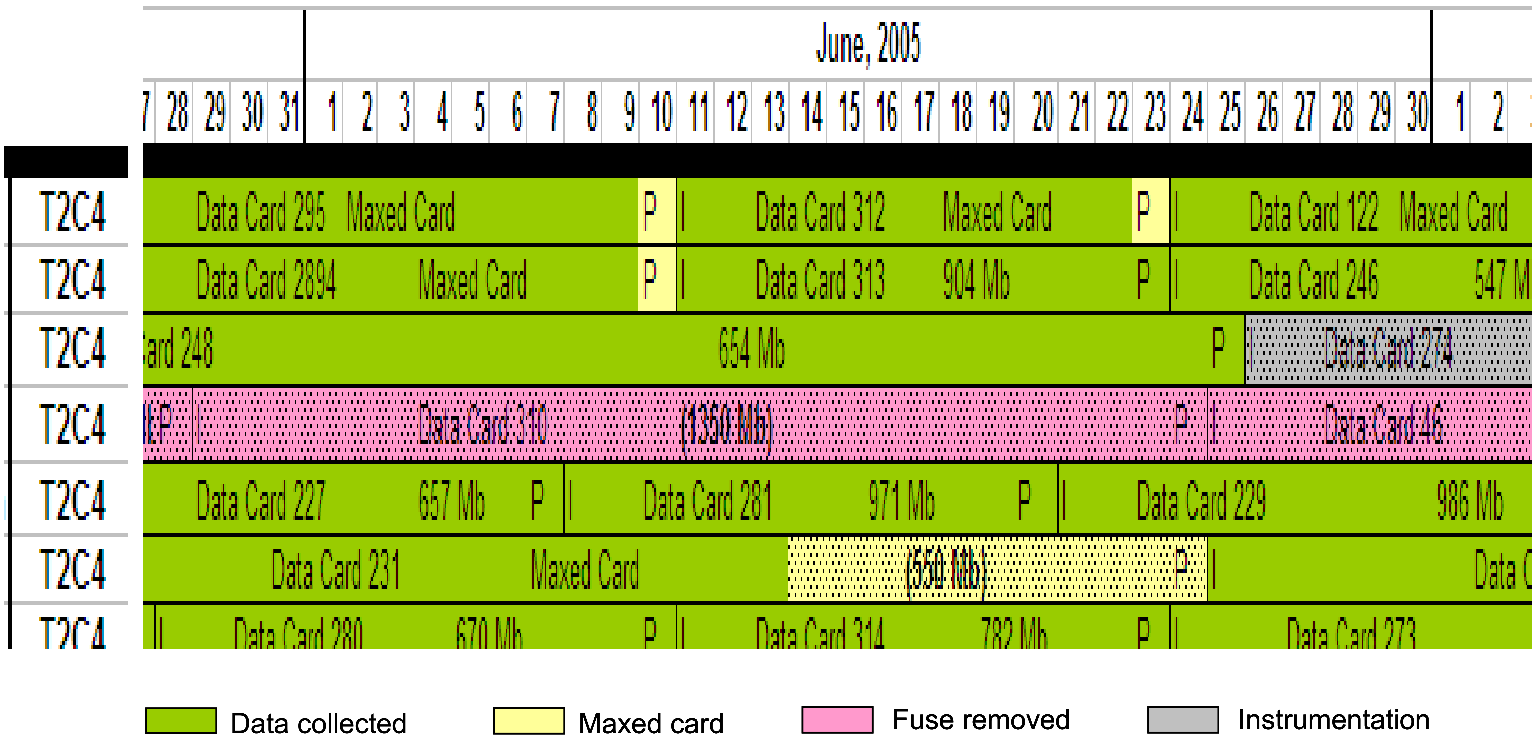


Figure 3-32. Visual Representation of the Data Collection Status using Data Card Information for Each Tractor as a Function of Time: Close-up View and Legend

Weekly Status Report

FOT Start Date		5/1/2005												
Report Date		11/1/2005												
	Vehicle Units		**DAS (# functional)**		**Data Channels**		**Data Cards Received**				**Vehicle Miles Traveled (VMT)**		**Odometer Miles Traveled**	**Data Quality**
							Total to Date		Weekly Total					
(Freightliner/Battelle)	Expected	Current	Expected	Current	Expected	Current	Non-Blank	Blank	Non-Blank	Blank	Actual to date	Weekly Total	Actual to date	Weekly Total	Percentage Passing Checks
T2C1 - Tractor	10	10	10	10	500	499	61	32	1	0	227,602	1	573,293	Not existing	100%
T2C2 - Tractor	10	10	10	10	500	490	61	15	1	0	288,735	3,936	527,794		98%
T2C3 - Tractor	10	10	10	10	500	498	77	16	4	0	255,436	17,852	528,121		100%
T2C4 - Tractor	9	9	9	9	450	435	76	14	0	0	313,562	2,819	449,890		97%
Subtotal T2 - Tractor	39	39	39	39	1950	1922	275	77	6	0	1,085,333	24,608	2,079,098		99%
T2C1 - Trailer	15	15	15	12	204	197	15	2	0	0	57,930	0	Not available		97%
T2C2 - Trailer	15	15	15	11	187	186	14	2	0	0	47,286	0			99%
T2C3 - Trailer	15	15	15	15	255	245	20	0	0	0	64,914	0			96%
T2C4 - Trailer	15	15	13	14	238	237	20	0	0	0	126,131	0			100%
Subtotal T2-Trailer	60	60	58	52	884	865	69	4	0	0	296,261	0			98%
T3 - Tractor/Trailer	8	8	8	8	496	490					160,621	9,945	527,709		99%
T3 - Tractor only							71	4	1	0	197,285	7,025			
Total	107	107	105	99			415	85	7	0	1,739,501	41,578	2,606,807		

	Valid Matched Data Miles Traveled					
	Expected to Date per Trailer configuration	Trailer Configuration				
		T2C1	T2C2	T2C3	T2C4	T3
T2C1 - Tractor	30,000	28	666	1,161	743	
T2C2 - Tractor	30,000	65	437	586	1,019	
T2C3 - Tractor	30,000	531	738	96	1,488	
T2C4 - Tractor	30,000	461	414	552	666	
Subtotal T2 - Tractor	120,000	1,085	2,256	2,395	3,917	
T2C1 - Trailer						
T2C2 - Trailer						
T2C3 - Trailer						
T2C4 - Trailer						
Subtotal T2-Trailer						
T3 - Tractor/Trailer	240,000					160,621
T3 - Tractor only						

Figure 3-33. Example of a Weekly Summary Report

Processes for data management described in earlier sections were instrumental to the automatic generation of weekly summaries and provided the Freightliner Team with timely knowledge of potential data collection issues in the field. The Freightliner Team implemented monthly trips to the Loveland facility to investigate and address concerns highlighted in the punchlist from data validation results. Upon resolution of the concern, the punchlist was updated.

Trailers were tracked by the Wal★Mart fleet, with the intention that the trailers be operated only within the Loveland service area. The Freightliner Team was also given access to the website for trailer tracking to assist in locating trailers when issues needed to be investigated. The Freightliner Team also assisted Wal★Mart, as appropriate, by pointing out trailers that had left the service area.

During the data collection period of the FOT, Wal★Mart fleet operational needs led to a few changes affecting the assignment of vehicles to home terminal or routes.

- Three tractors were transferred from the Loveland distribution center to another center located in Grantsville, Utah. One of the three drivers volunteered to remove and replace data cards on these three tractors. Upon his occasional return to the Loveland terminal, the driver exchanged the full data cards with empty ones.
- At the end of the first period of dedicated routes, after the first 6 months, the dedicated routes were reorganized to meet operational needs. As a result, one of original dedicated stores was no longer supplied from Loveland. Two drivers were originally assigned to this store and the associated dedicated route. Since the route was not replaced by another route, these two drivers were reassigned to other non-dedicated routes, and their vehicles, originally tagged as T3 configurations, were treated for data management purposes as T2C3 tractors. The date at which they discontinued driving their dedicated route to the given store was recorded, and all data received from this date on was included in the Template 2 data rather than the Template 3 data.

All information regarding vehicle reassignments was carefully tracked for each vehicle and shared with the IE using vehicle codes.

The Freightliner Team processed the data uploaded to transfer them to the IE. Data and accompanying data summary tables were shipped to the IE on DVDs in the following installments during Phase 1:

- July 22, 2005 (9 DVDs)
- July 27, 2005 (1 DVD with updated data parser)
- September 9, 2005 (17 DVDs)
- September 21, 2005 (8 DVDs)
- October 7, 2005 (7 DVDs)
- November 4, 2005 (14 DVDs)
- November 10 and 11, 2005 (4 DVDs)
- December 19, 2005 (12 DVDs).

Upon receipt of the DVDs, the IE conducted its own data management routines. The Freightliner Team, as requested, assisted the IE by addressing questions and modifying internal processes as necessary.

3.3.3.3 USDOT Briefing

As the data collection for Phase 1 neared completion, a briefing was held in Washington State on October 19-20, 2005, with representatives of the USDOT, the IE, and members of the Freightliner Team, including Freightliner and Battelle. The objective of the meeting was to review the current state of data collection, data analysis, and FOT objectives as the project moved forward.

3.3.3.4 Activation of Enabled Technologies for Phase 2

As prescribed by the FOT test plan (Freightliner 2005), enabled safety technologies were activated after 6 months of data collection. Table 3-14 highlights the technologies that were activated for each tractor and trailer configuration. In Template 2, Configuration 4 tractors and Configurations 1 and 2 trailers did not have any enabled safety technologies activated by design.

Descriptions of the technologies and associated manufacturer are included in Section 2 of this report.

Table 3-14. Enabled Technologies Activated for Phase 2 as a Function of Tractor and Trailer Configuration. Enabled Technologies are Shown in Bold Blue Underlined Font, while Phase 1 Technologies are Shown in Black Italics Font.

	Tractors	**Trailers**
Template 2 – Config. 1	*AM drum brakes* *MW ABS* **Adaptive Cruise Control (ABS)** **Roll Stability Control (RSC)**	*AM drum brakes* *MW ABS*
Template 2 – Config. 2	*BK disc brakes* *MW ABS* **Adaptive Cruise Control (ABS)** **Roll Stability Control (RSC)**	*AM disc brakes* *MW ABS*
Template 2 – Config. 3 **Template 3**	*BK disc brakes* *MW ECBS* **Adaptive Cruise Control (ECBS)** **Electronic Stability Control (ESC)**	*BK disc brakes* *MW ECBS* **Roll Stability Support (RSS)**
Template 2 – Config. 4	*BK disc brakes* *Bendix ABS6*	*BK disc brakes* *Bendix ECBS* **Trailer Roll Stability (TRSP)**

BK: Bendix Knorr; MW: Meritor WABCO; AM: Arvin Meritor

Manufacturers of the technologies were responsible for technology activation on tractors and trailers, and their representatives traveled to Loveland for this purpose. As with similar activities in this FOT, checklists were developed and implemented for use in the field. Most vehicles were activated by Meritor WABCO and Bendix representatives: trained Wal★Mart staff also contributed to the efforts by activating vehicles that were available after the vendors' visits to Loveland.

The activation was scheduled in stages to facilitate logistics of having multiple vendors on site as well as to accommodate validation activities conducted on the ACC technology at the Freightliner Test Center before the activation. In Stage 1, trailer-based technologies were enabled by Bendix. In December 2005, Bendix began activation the TRSP technology on the T2C4 trailers. Two trailers were activated by Wal★Mart as they returned to the terminal at a later date. At the time of their visit, Bendix representatives also inspected the T2C4 tractors that were on site, although no technology was activated. In Stage 2, Meritor WABCO representatives began activating the 55 T2C3 and T3 trailers with the RSS technology. Similarly with the Bendix trailers, trailers that were not available at the time were subsequently activated by trained Wal★Mart staff. In Stage 2, Meritor WABCO also activated the ECBS-enabled technologies on T2C3 and T3 tractors, namely the ACC and ESC technologies. Finally, in Stage 3, Meritor WABCO activated the ABS-based enabled technologies, RSC and ACC, on T2C1 and T2C2 tractors.

Issues encountered upon activation of the technologies included the need to reprogram the engine ECU on selected tractors to enable the ACC parameter. Work unrelated to the FOT had been done at the dealership on these specific tractors, with the result that the engine ECU required reprogramming. The ACC parameter, not being a standard parameter for Wal★Mart, was erased in the process. Meritor WABCO identified this problem during test drives on these tractors after activation. The Detroit Diesel dealership was contacted and requested to promptly correct the situation. Dates of reprogramming were communicated to the Freightliner Team upon request and were taken into consideration for actual activation of the ACC technology on these tractors.

All activation activities and efforts were closely managed, tracked, and supervised by the Freightliner Team. The date of technology activation was recorded for each vehicle, and stored in the FOT database for further processing of the data into Phase 1 and Phase 2 bins. The CSV table of activation dates for each tractor was also provided to the IE. Because of the complexity of the experimental design and associated evaluation objectives, the start date could potentially vary for each individual vehicle as a function of the evaluation topic. As such, as shown in Figure 3-34, several Phase 2 start dates were specified. Details and results of this process were shared with the IE. Data were stored in the FOT database accordingly for follow-on processing activities.

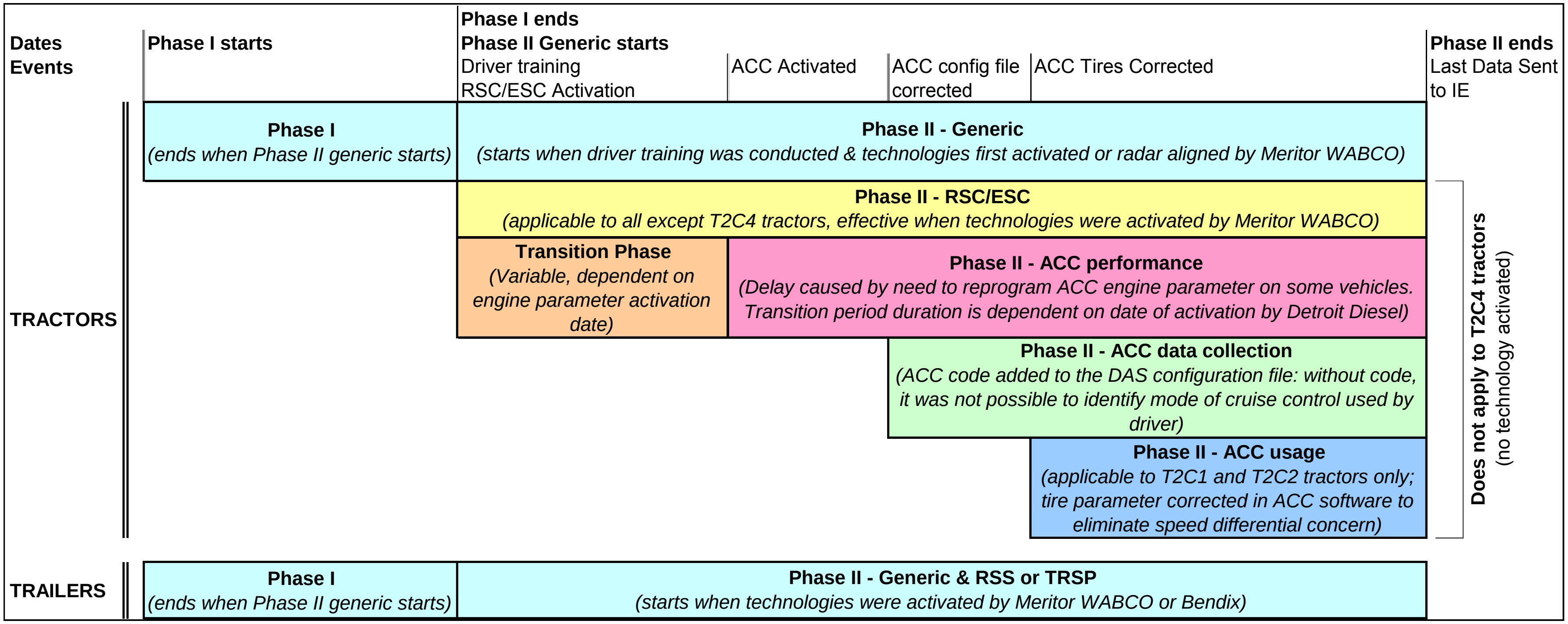


Figure 3-34. Definitions used for Determining Phase 2 Start Dates

3.3.3.5 Phase 2 Driver Training

As the technologies were activated on the vehicles, the Freightliner Team organized a second training program to train drivers on the enabled technologies activated for Phase 2. Appendix F includes the training brochures developed by the Freightliner Team. As only a subset of drivers could attend the in-class sessions, the Freightliner Team produced training DVDs for the drivers. Copies of the DVDs were provided to the fleet operator and drivers were asked to view the videos upon return to the terminal on their day-out.

3.3.3.6 Phase 1 Surveys

The Freightliner Team conducted a second set of surveys of both drivers and technicians before they were exposed to the enabled technologies.

3.3.3.7 Phase 1 Maintenance Records

The Freightliner Team collected maintenance records as described earlier for the first phase of the vehicle and technology use in the field. Records were sanitized and sent to the IE.

3.3.3.8 Phase 2 Data Collection

For Phase 2, collection of onboard data was officially started as the technologies were activated and functioning on each individual vehicle. As such, between Phase 1, during which all vehicles operated without any enabled technologies, and Phase 2, during which all vehicles operated with enabled technologies, a transition phase was created. In this transition, some vehicles were operating in Phase 2 while others remained operating in Phase 1.

Similarly to Phase 1 data collection, the Freightliner Team used all processes described earlier to collect, upload, store, validate, and transfer the onboard data to the IE. In parallel to onboard data collection, maintenance and survey data were also collected at appropriate times.

Issues that were raised in the field were addressed and resolved as needed. For example, drivers pointed out the presence of a speed differential between the speeds displayed on the vehicle speedometer and on the ACC display screen. Upon investigation of the issue, Meritor WABCO identified the origin of the speed difference and corrected the problem by changing a parameter in the ACC software. As the team was trying to quantify the extent to which drivers were utilizing ACC or CCC with the onboard data collected starting from the date of activation, the Team discovered that a key parameter, the ACC_mode, was incorrectly omitted from the data file collected onboard the tractors. Aberdeen Test Center promptly, upon request, corrected the error in each configuration file, and the Freightliner Team reloaded the revised configuration files on each tractor.

Throughout the collection of onboard data, the Freightliner Team continued to work closely with Wal★Mart staff to encourage the timely removal of data cards from the vehicle, hence limiting the loss of data as a result of full data card capacity. As data were uploaded, validated, and stored on the Battelle server, the Freightliner Team continued to generate data summaries that were sent to the USDOT and the IE. An example of the Phase 2 data summaries is included in Section 4.

The Freightliner Team processed the data uploaded to transfer them to the IE. Data and accompanying data summary tables were shipped to the IE on DVDs in the following installments during Phase 2:

- January 12, 2006 (13 DVDs)
- February 6, 2006 (15 DVDs)
- February 16, 2006 (2 DVDs)
- March 7, 2006 (7 DVDs)
- March 22, 2006 (9 DVDs)
- April 11, 2006 (7 DVDs)
- May July 27, 2006 (15 DVDs).

Upon receipt of the DVDs, the IE conducted its own data management routines. The Freightliner Team, as requested, assisted the IE by addressing questions and modifying internal processes as necessary.

3.3.3.9 Phase 2 Surveys

Once the data collection period of the FOT was completed on April 30, 2006, the Freightliner Team conducted a final set of surveys of both drivers and technicians.

3.3.3.10 Phase 2 Maintenance Records

The Freightliner Team collected maintenance records generated during the second phase of the FOT. Upon review of the maintenance records obtained from Phase 1, the IE did not request changes to the maintenance data collection.

The Freightliner Team, specifically representatives from Bendix, also inspected the brake systems on a subset of tractors and trailers, including wear measurements of the brake components of disc and drum brakes. A summary and analysis of the brake inspection activity is scheduled to be created by the IE.

3.3.4 Vehicle Instrumentation Decommissioning

Once the data collection period of the FOT was completed on April 30, 2006, the Freightliner Team prepared to decommission the instrumentation on the tractors and trailers. Only systems installed for the purpose of data collection were subject to decommissioning. Per the field test agreement between Wal★Mart and Freightliner as well as in accordance with the cooperative agreement, safety technologies were not removed from the vehicles.

Instructions were drafted by the Freightliner Team, tested on two vehicles in the field in August 2006, revised as appropriate, and finalized for the complete decommissioning of the vehicles. QC documents were developed and implemented. Members of the Freightliner Team collaborated to ensure that the decommissioning strategy and implementation were acceptable to all parties, in particular to Wal★Mart as owner of the vehicles.

Hardware, including DAS units, mini-DAS units, video DAS units, pressure transducers, steering angle sensors, and GPS antennas, were sent to the Aberdeen Test Center per USDOT's instructions.

The IE witnessed the decommissioning activities as they took place in early October 2006.

3.4 Task 5: Progress Reporting

Task 5 was dedicated to progress reporting as detailed in the cooperative agreement (USDOT 2003).

4.0 DATA SUMMARIES

As the Team conducting the tests on this project, the Freightliner Team was not tasked with any activities dealing with data analysis other than validation. Consequently, analysis results are not included in this report, but are schedule to be published under separate cover by the IE upon completion of the evaluation of ECBS and enabled technologies. This section presents only an overview of data summaries generated by the Freightliner Team within the scope of the FOT.

4.1 Onboard Data Summary

As described previously, the Freightliner Team produced data summary reports on a weekly basis to track the status of the data collection and validate the data received. The data summaries were updated weekly upon upload of the data cards received from the field. A final data summary was produced upon completion of the data collection period of the FOT. The data summary, dated July 26, 2006, is shown in Figure 4-1 along with definitions of terms used in the summary report.

Data were collected over a total of 4,382,712 miles of travel during the ECBS FOT on the FOT tractors and trailers in Template 2 and 3 combined. Data were collected over a total of 144,844 miles on the baseline profiling tractors.

Weekly Status Report																
FOT Start Date	5/1/2005															
Report Date	7/26/2006															
	Study Phase	Vehicle Units		DAS (# functional)		Data Channels		Data Cards Received				Vehicle Miles Traveled (VMT)		Odometer Miles Traveled		Data Quality
								Total to Date		Weekly Total						
(Freightliner/Battelle)		Expected	Current	Expected	Current	Expected	Current	Non-Blank	Blank	Non-Blank	Blank	Actual to date	Weekly Total	Actual to date	Weekly Total	Percentage Passing Checks
T2C1 - Tractor	1	10	0	10		300		125	46	0	0	460,866	0	909,475	Not existing	
	2		8		6		264	85	22	24	5	229,983	73,496	285,186		88%
T2C2 - Tractor	1	10	1	10	1	500	47	126	16	2	0	591,303	13,348	1,070,745		94%
	2		9		9		432	65	8	20	0	205,802	70,779	335,903		96%
T2C3 - Tractor	1	10	1	10	1	350	50	126	29	3	0	470,286	25,123	901,854		100%
	2		9		6		285	68	17	19	8	240,439	70,988	283,282		95%
T2C4 - Tractor	1	9	0	9		400		128	30	1	0	528,968	0	712,095		
	2		9		8		390	87	9	25	4	283,225	91,441	328,834		98%
Subtotal T2 - Tractor	1	39	2	39	2	1550	97	505	121	6	0	2,051,423	38,472	3,594,168		97%
	2		35		29		1371	305	56	88	17	959,448	306,704	1,233,206		95%
T2C1 - Trailer	1	15	15	15	11	187	167	32	8	1	0	115,772	528	Not available		89%
	2									0	0		0			
T2C2 - Trailer	1	15	15	15	8	136	131	24	14	2	0	86,025	6,665			96%
	2									0	0		0			
T2C3 - Trailer	1	15	2	15		221		25	0	0	0	127,713	12,859			
	2		13		13		200	14	3	2	0	47,599	12,268			90%
T2C4 - Trailer	1	15	1	15		187		26	0	0	0	197,064	8,724			
	2		14		11		186	14	8	1	0	23,547	973			99%
Subtotal T2-Trailer	1	60	33	60	19	731	298	107	22	3	0	526,574	28,776			92%
	2		27		24		386	28	11	3	0	71,146	13,242			95%
T3 - Tractor/Trailer	1	8	0	8	0	0		114	11	0	0	235,495	0	795,423		
T3 - Tractor only												315,752	0			
T3 - Tractor/Trailer	2		8		7	434	428	53	8	20	1	29,529	0	312,409		99%
T3 - Tractor only												193,345	99,994			
Total		107	105	107	81			1,112	229	120	18	4,382,712	487,187	5,935,206		

Vehicle Units	The number of vehicle units (tractors, trailers) that are in this phase
DAS (# functional)	The last data card received was a non-zero card
Data channels	
Expected	Expected number of functional data channels per configuration in terms of recorded data values
Actual	Actual number of data channels per configuration producing valid data in terms of recorded data values
Data cards received	
Total to date	Total number of data cards retrieved from May 2005 to date of report
Weekly total	Total cards retrieved for the week of the report
Non-Blank	The number of data cards retrieved by Battelle from Wal★Mart with blob data on them
Blank	The number of data cards retrieved by Battelle from Wal★Mart with no blob data on them
VMT	Vehicle miles traveled (collected)
Actual	VMT, as indicated by the data collected to date, i.e. from start of test, May 2005, to the date of the report
Weekly total	VMT for the week of the report based on the data card processed date
Odometer Miles Traveled	The number of VMT, based upon odometer readings
Data Quality	Percent of channels recorded by the functional DAS in service that are producing valid data
Miles Sent To IE	The quantity of tractor VMT sent to the Independent Evaluator

Figure 4-1. Final Data Summary Report, with Definitions

Table 4-1 lists the tractor VMT recorded as a function of vehicle configuration and study phase for Template 2 and Template 3 tractors.

- Data were collected over a total of 3,784,991 miles of travel.
- In Template 2, data were collected over a total of 3,010,871 miles in Phases 1 and 2 of the FOT on the four configurations of tractors, consisting of 2,051,423 miles in Phase 1 and 959,448 miles in Phase 2.
- In Template 3, data were collected over a total of 774,120 miles, consisting of 551,247 miles in Phase 1 and 222,873 miles in Phase 2.

Table 4-1. VMT Collected for Template 2 and Template 3 Tractors per Configuration and Study Phase

Tractor Configuration	Study Phase		Total
	1	2	
T2C1	460,866	229,982	690,848
T2C2	591,303	205,802	797,105
T2C3	470,286	240,439	710,725
T2C4	528,968	283,225	812,193
Template 2 Total	2,051,423	959,448	3,010,871
Template 3	551,247	222,873	774,120
Total	2,602,670	1,182,321	3,784,991

These data mileages take into consideration the data collected from the two tractors originally assigned to Template 3 that were transferred to Template 2 (T2C3) after the first 6 months of operation from one of the Template 3 dedicated routes.

Table 4-2 lists the trailer VMT recorded as a function of trailer configuration and study phase for Template 2 and Template 3. Since the experimental design called for no enabled technologies to be activated on the T2C1 and T2C2 trailers, all VMT recorded is labeled Phase 1.

- Data were collected over a total of 862,744 trailer miles of travel.
- In Template 2, data were collected over 597,720 miles of travel in Phases 1 and 2 of the FOT on the four configurations of trailers, consisting of 526,574 miles in Phase 1 and 71,146 miles in Phase 2.

- In Template 3, data were collected over 265,024 miles of travel in Phases 1 and 2, consisting of 235,495 miles in Phase 1 and 29,529 miles in Phase 2.

Table 4-2. VMT Collected for Template 2 and Template 3 Trailers per Configuration and Study Phase

Trailer Configuration	Study Phase		Total
	1	2	
T2C1	115,772	-	115,772
T2C2	86,025	-	86,025
T2C3	127,713	47,599	175,312
T2C4	197,064	23,547	220,611
Template 2 Total	526,574	71,146	597,720
Template 3	235,495	29,529	265,024
Total	762,069	100,675	862,744

Tractor and trailer data were matched using processes described in section 3.2.6.1.

Template 2 tractors blob files ("blobs") were matched to Template 2 trailer blobs based on GPS and time data. To be considered matched, the GPS data contained in both the tractor and the trailer blobs must indicate that the tractor and trailer are within 50 ft in both latitude and longitude; and the time must be within 60 seconds. Figure 4-2 illustrates samples of matched and unmatched blobs by plotting the starting odometer value of each tractor blob as a function of the start time of the blob. Each marker in the plots represents a blob file. Tractor blobs matched to trailer blobs are shown in red markers.

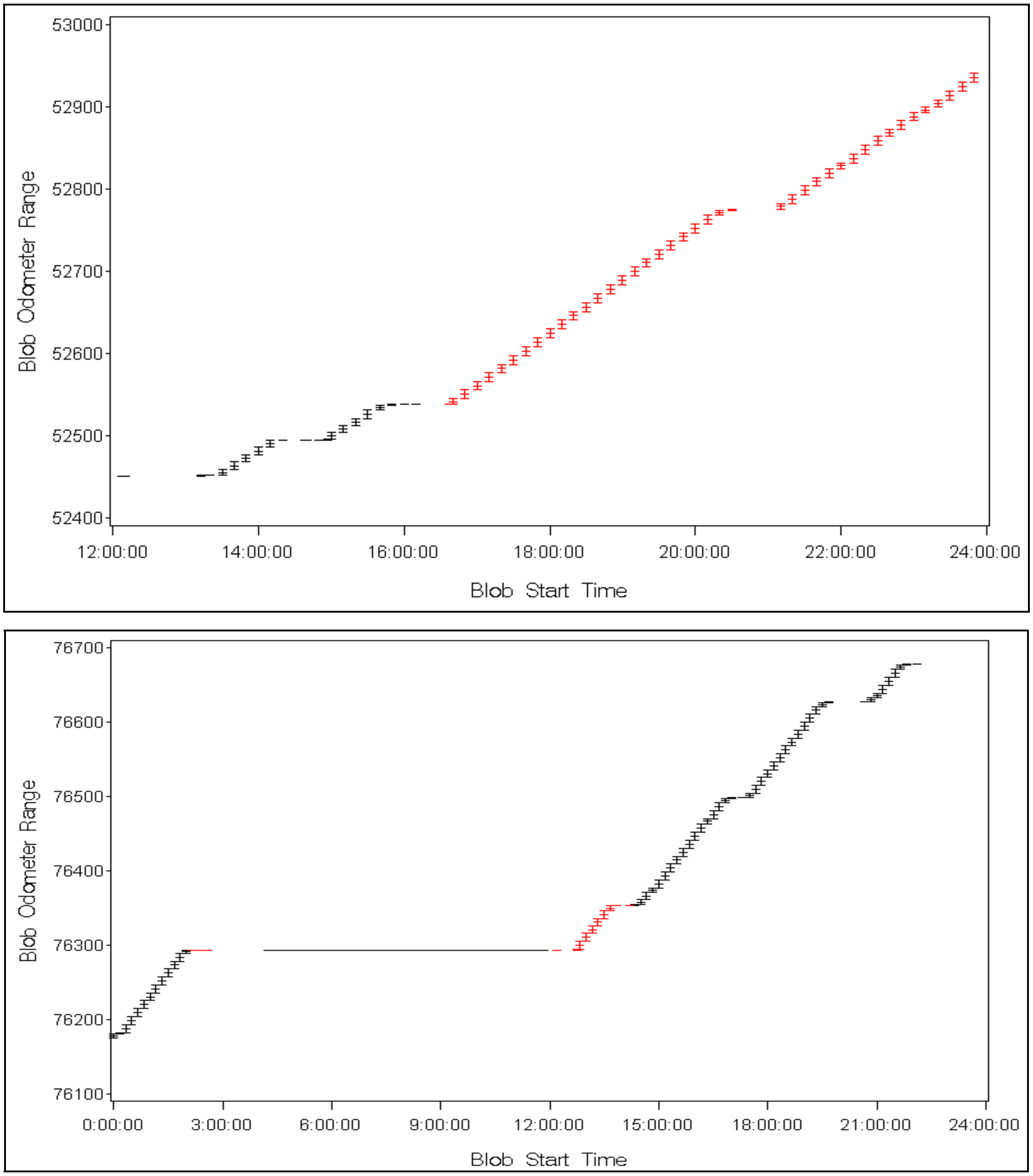


Figure 4-2. Visual Representations of Matched and Unmatched Blobs for Two Template 2 Tractors

Figure note: Each Blob is Represented by a Marker, in Red if it is Matched to a Trailer Blob and in Black if it is not Matched.

Template 3 tractor blobs were matched to Template 3 trailer blobs based on trailer data directly recorded in the tractor blob. Table 4-3 lists the number of miles collected for tractors matched or unmatched with Template 2 trailers. Despite all efforts to maintain the Template 2 vehicles within a sub-fleet, the nature of the fleet operation along with the large quantity of vehicles operated from the Loveland terminal resulted in low matching numbers of Template 2 tractors with Template 2 trailers. Most of the data collected were for Template 2 tractors pulling conventional ABS drum brake trailers, with which any tractor equipped with novel technologies has to be compatible. As such, the data collected still provide valuable insights.

Table 4-3. VMT Collected for Tractors Matched or Unmatched to Template 2 Trailers, per Template, Configuration and Study Phase

Configuration	Study Phase				Total
	1		2		
	Matched	Unmatched	Matched	Unmatched	
T2C1	5,076	455,790	380	229,602	690,848
T2C2	4,579	586,724	403	205,399	797,105
T2C3	5,933	464,353	852	239,587	710,725
T2C4	6,335	522,633	1,121	282,103	812,192
Template 2 Total	21,923	2,029,500	2,756	956,691	3,010,870
Template 3	32,414	518,833	3,621	219,253	774,121
Total	54,337	2,548,333	6,377	1,175,944	3,784,991

Note: The Miles Collected for Template 3 Tractors Matched to Template 3 Trailers are not Included as Matched in this Table.

From a technology standpoint, the configuration of Template 2 Configuration 3 and Template 3 vehicles is identical. As such, data collected onboard a Template 3 tractor not operating in an optimized manner by pulling a T3 trailer can be binned as Template 2 Configuration 3 tractor data. Table 4-4 summarizes data miles collected, with non-optimized Template 3 tractor data binned as T2C3 data. Thus, the quantity of Template 3 data in Table 4-4 (235,495 and 29,529 miles for Phases 1 and 2, respectively) represents only when a T3 tractor was pulling a T3 trailer. The IE may choose to categorize the data in this manner for evaluation of the optimized performance of the ECBS technologies.

Table 4-4. VMT Collected for Template 2 and Template 3 Tractors per Configuration and Study Phase

Tractor Configuration	Study Phase		Total
	1	2	
T2C1	460,866	229,982	690,848
T2C2	591,303	205,802	797,105
T2C3	786,038	433,783	1,219,821
T2C4	528,968	283,225	812,193
Template 2 Total	2,367,175	1,152,792	3,519,967
Template 3	235,495	29,529	265,024
Total	2,602,670	1,108,163	3,784,991

Note: Unmatched Template 3 Data are Shown as T2C3 Data

Using the GPS data found in the data file header, the Freightliner Team collected the data as a function of time of the day, as shown in Table 4-5. These data can be used by the IE to investigate the benefits of technologies as a function of day or night driving.

Table 4-5. VMT Collected for Template 2 and Template 3 Tractors per Configuration, Study Phase, and Time of Day

Configuration	Study Phase							
	1				2			
	Dawn	Day	Dusk	Night	Dawn	Day	Dusk	Night
T2C1	3,922	301,873	4,895	150,176	1,197	154,941	682	73,162
T2C2	4,614	429,869	3,890	152,929	274	129,341	1,009	75,178
T2C3	5,992	348,113	3,483	112,698	2,369	168,350	350	69,370
T2C4	3,587	357,753	3,639	163,989	1,675	148,612	2,880	130,058
Template 2 Total	18,115	1,437,608	15,907	579,792	5,515	601,244	4,921	347,768
Template 3	2,463	405,817	2,625	140,342	485	144,454	332	77,603
Total	20,578	1,843,425	18,532	720,134	6,000	745,698	5,253	425,361

Note: The source of the algorithm used was the Almanac for Computers, 1990 published by Nautical Almanac Office, United States Naval Observatory Washington, DC 20392

The following definitions were used to categorize the data collected as a function of time of day, namely dawn, day, dusk, or night.

- Dawn (civil): The time at which the sun is 6 degrees below the horizon in the morning
- Sunrise: The time at which the first part of the sun breaks the horizon
- Sunset: The time at which the last part of the sun dips below the horizon
- Dusk (civil): The time at which the sun is 6 degrees below the horizon in the evening.

The dawn and dusk driving periods each represent approximately 30 minutes of driving per day. The day and night periods represent differing durations dependent on the time of year, e.g., day is longer in the northern hemisphere during the summer months. However, on balance the day and night periods represent approximately equal durations. The breakdown of driving mileage by period of day illustrates the propensity of the Wal★Mart fleet operations to cover more mileage during the day than the night, as expected. Further analysis of the time of day would likely indicate that most of the night driving occurs in the time shortly before dawn and shortly after dusk.

As described earlier, enabled technologies were activated upon completion of Phase 1. Dates of activation, for selected technologies and corresponding vehicles, varied from vehicle to vehicle. Hence, the quantity of data collected for each vehicle configuration was calculated as a function of the end use of the data. For example, since RSC was generally activated earlier than ACC on T2C1 and T2C2 tractors, more data are available to investigate evaluation research questions targeted to the RSC technology. Table 4-6 lists all mileage collected as a function of the objectives of the evaluation. Phase 2 was subdivided into several sub-phases as detailed earlier in Figure 3-34:

- Phase 2 Generic started when the driver training was conducted and technologies were first activated or radar was aligned by Meritor WABCO
- Phase 2 RSC/ESC phase, applicable to all tractors except T2C4 tractors, was effective when the RSC or ESC technologies were first activated by Meritor WABCO
- Transition phase was variable and was dependent on the engine parameter activation date
- Phase 2 ACC performance was the phase during which ACC was activated and working on the tractors

- Phase 2 ACC data collection was the phase for which the specific data code identifying the mode of cruise control used by the driver was added to the DAS configuration file
- Phase 2 ACC usage, only applicable to T2C1 and T2C2 tractors, defined the phase for which concerns of speed differential caused by an incorrect parameter in the ACC ECU were eliminated.

The dates each individual tractor transitioned between the sub-phases identified in Table 4-6 have been provided to the IE to assist in its evaluation of the various research objectives.

Table 4-6. VMT Collected for Template 2 and Template 3 Tractors per Configuration and Study Phase as Defined by Evaluation Objective

Configuration	Study Phase					
	Phase 1	Phase 2				
		Generic, RSC / ESC	Transition	ACC Performance	ACC Data Collection	ACC Usage
T2C1	460,596	230,253	270	229,982	110,276	86,236
T2C2	492,035	236,059	30,257	205,802	122,259	84,419
T2C3	443,209	267,507	27,068	240,439	109,355	109,355
T2C4	528,968	283,225	0	283,225	283,225	283,225
Template 2 Total	1,924,808	1,017,044	57,595	959,448	625,115	563,235
Template 3	533,271	240,849	17,976	222,873	121,378	121,378
Total	2,458,080	1,257,893	75,571	1,182,321	746,493	684,613

4.2 Vehicle Dispatch

The operation of the FOT tractors and trailers for which data were collected is shown in Figure 4-3 and 4-4, respectively. Although some vehicles were operated outside of the Loveland distribution center service area, most of the traffic was concentrated around Loveland. Figure 4-5 shows the routes used by Template 3 tractors only, illustrating the concentration of trips on dedicated routes. Figure 4-6 illustrates the locations of the Wal★Mart distribution centers in the United States. In Wal★Mart's typical operations, trailers are not domiciled in one distribution center but are used throughout the country on an as-needed basis. The efforts of all members of the Freightliner Team can be seen on Figure 4-4, as the FOT trailers remained centralized around Loveland.

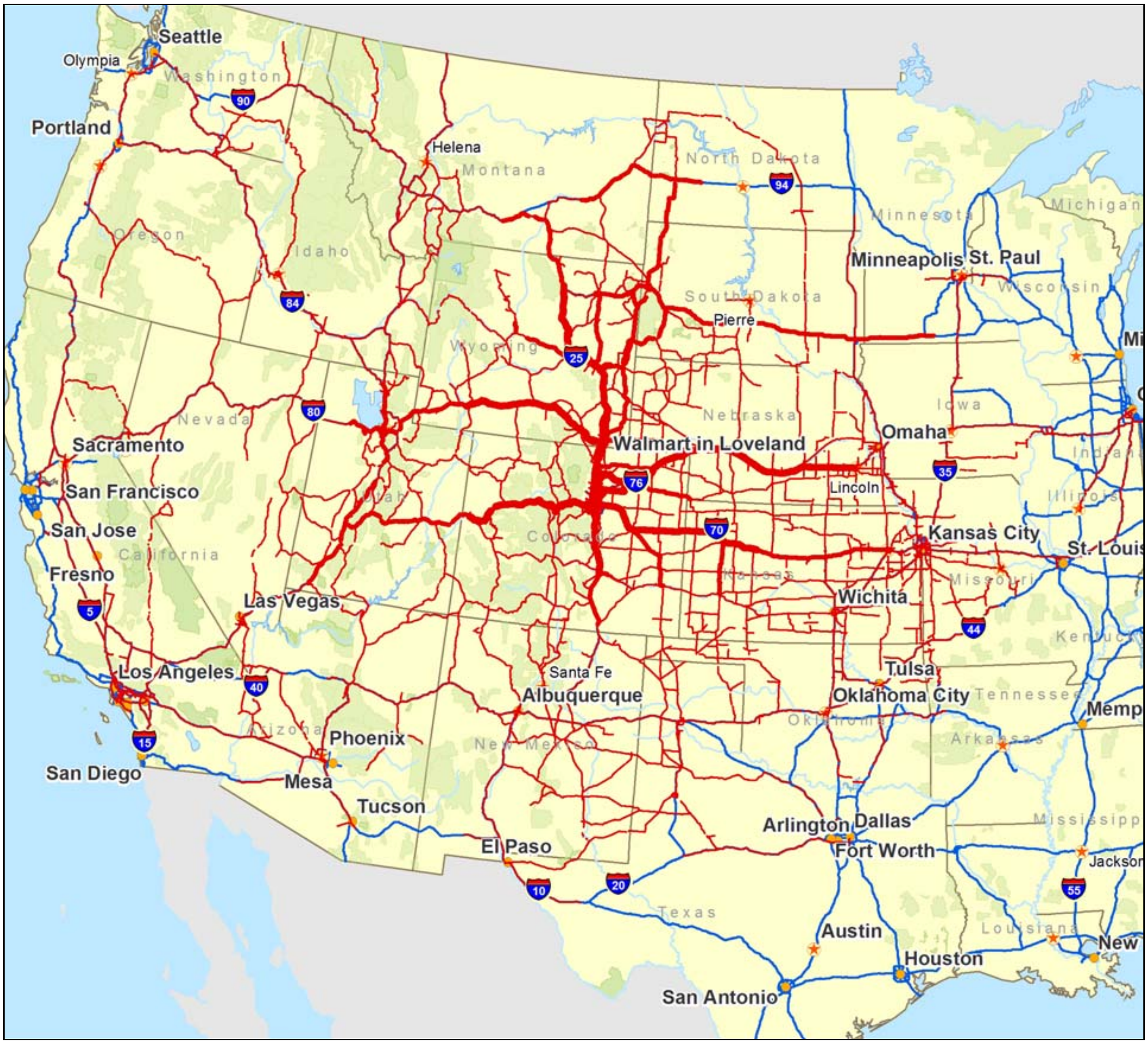


Figure 4-3. Operation of the Template 2 and Template 3 Tractors during Data Collection. Road Usage is Proportional to the Line Thickness.

Figure 4-4. Operation of the Template 2 and Template 3 Trailers during Data Collection. Road Usage is Proportional to the Line Thickness.

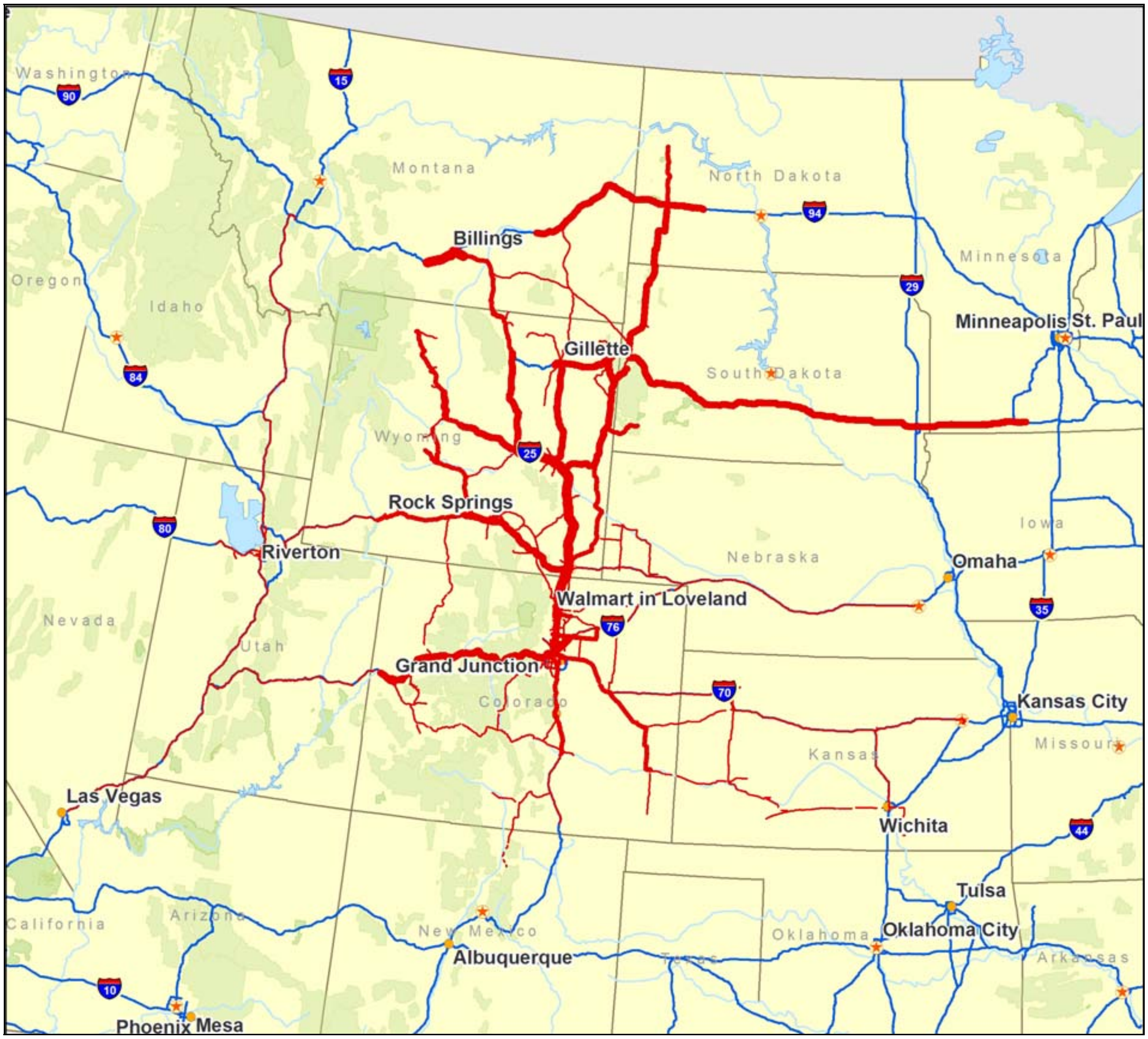


Figure 4-5. Operation of the Template 3 Tractors during Data Collection. Road Usage is Proportional to the Line Thickness.

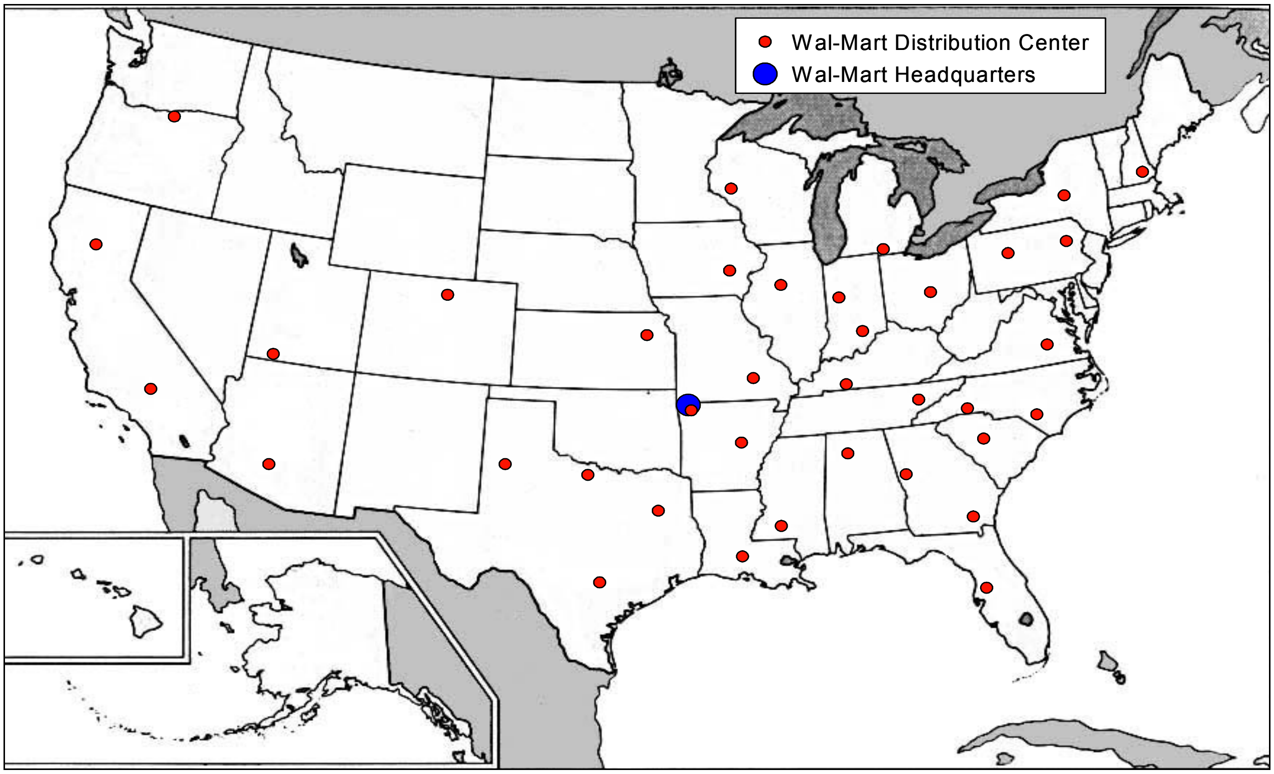


Figure 4-6. Location of the Wal★Mart Distribution Centers

4.3 Summary Statistics & Onboard Data Characterization

The Freightliner Team computed summary statistics of the data after they were collected and validated. The following section presents results of the summary statistics with the sole intent and purpose to describe and characterize in general terms the operating characteristics observed during the FOT. Results or conclusions related to the evaluation objectives of the FOT are not drawn from the summary statistics presented, because these are within the scope of the IE's analyses of the data.

Vehicle Speed

Table 4-7 lists the average tractor road speeds (mph) as a function of vehicle configuration and study phase. For this analysis, Phases 1 and 2 data were defined by the generic Phase 2. As described in section 4.1, the generic phase 2 period starts when the driver training was conducted and technologies were first activated or radar was aligned by Meritor WABCO.

Table 4-7. Average Road Speed of Tractors in Templates 2 and 3 per Study Phase

Configuration	Average Road Speed in mph (95%Confidence Interval)	
	Phase 1	Phase 2
T2C1	48.85 (47.68, 50.02)	47.77 (46.57, 48.96)
T2C2	49.39 (47.87, 50.90)	48.53 (47.00, 50.06)
T2C3	47.03 (45.73, 48.33)	47.40 (46.07, 48.72)
T2C4	48.35 (47.44, 49.26)	48.61 (47.67, 49.54)
T3	48.93 (47.93, 49.94)	48.41 (47.37, 49.45)

Note: 95 Percent Confidence Intervals Shown in Parenthesis take into Consideration Truck-to-truck Variability.

Figure 4-7 illustrates the average road speed of the tractors as a function of template, vehicle configuration and study phase. From Table 4-7 and Figure 4-7, it can be concluded that the average speed behaviors of drivers assigned to all five configurations of vehicles are similar. Although there appears to be a drop in the average speed during Phase 2 for the T2C1 and T2C2 configurations, this change is not statistically significant.

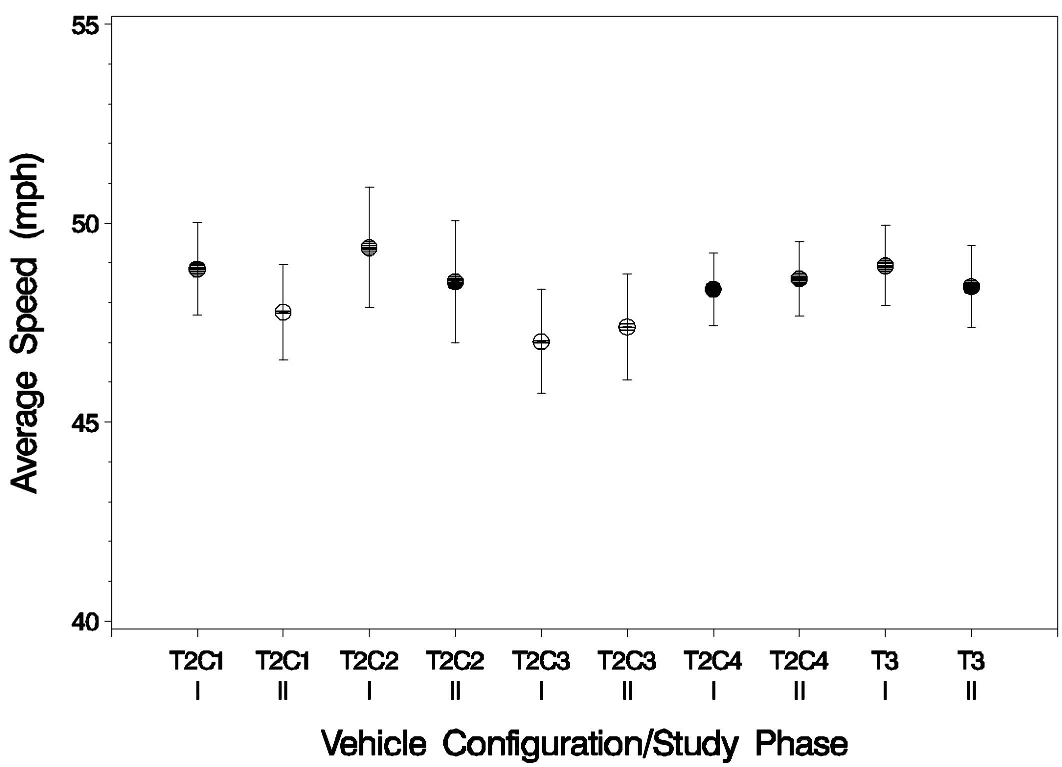


Figure 4-7. Average Vehicle Speed (mph)

<u>Elevation and Road Slope</u>

Table 4-8 summarizes the average tractor elevations (meters) as a function of vehicle configuration and study phase. On average, Template 3 tractors were operated at a higher average elevation. For this analysis, Phases 1 and 2 were defined by Phase 2 generic. As described in Section 4.1, the generic Phase 2 period started when the driver training was conducted and technologies were first activated or radar was aligned by Meritor WABCO.

Table 4-8. Average Elevation (m) of Tractors in Templates 2 and 3 as a Function of Study Phase

Configuration	Average Elevation (m)	
	Phase 1	Phase 2
T2C1	1,473	1,497
T2C2	1,459	1,506
T2C3	1,451	1,503
T2C4	1,442	1,474
T3	1,627	1,453

Figure 4-8 illustrates the distribution of average elevation for Template 2 (black line) and Template 3 (red line) tractors. The observed elevations for Template 2 and 3 tractors is consistent with the maps provided in Figure 4-3 and 4-5. Figure 4-5 illustrates that the majority of Template 3 driving was conducted in the high-elevation area due north of the Loveland distribution center, whereas Figure 4-3 illustrates that when all tractors are considered, there are more trips to lower elevation areas south and east of the Loveland distribution center. The variation in the average elevation of Template 3 tractors in Phases 1 and 2 may be due to the changes in dedicated routes every 6 months.

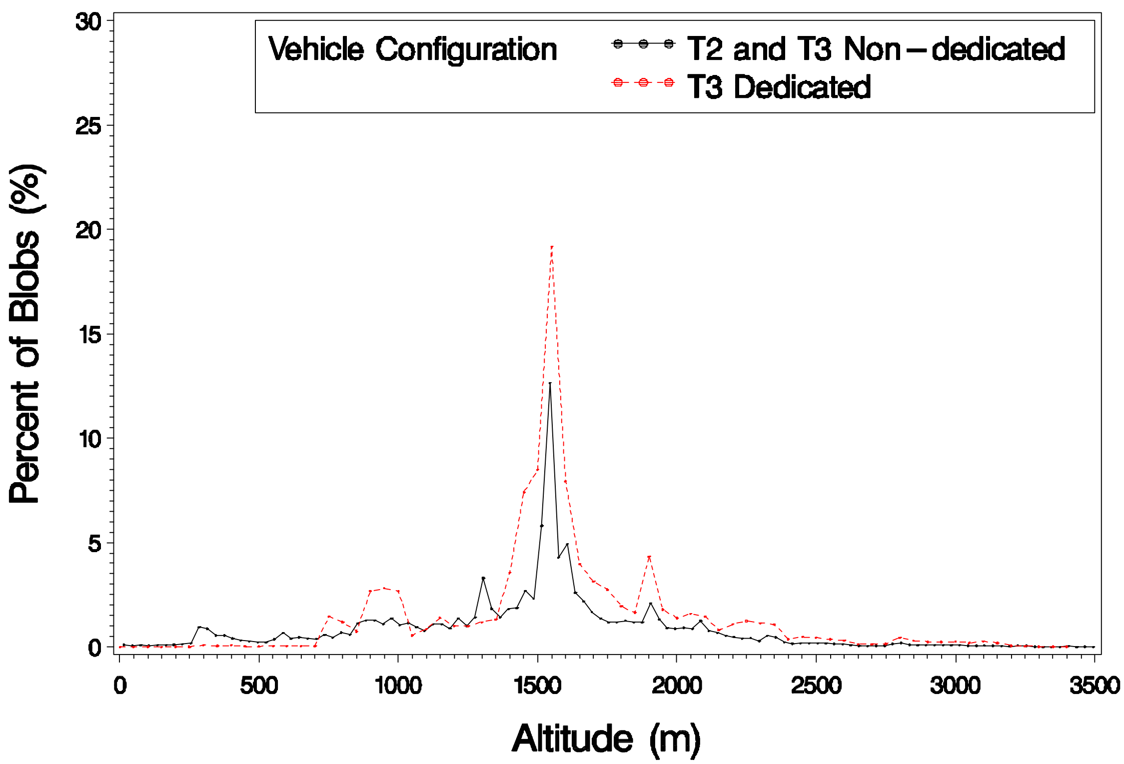


Figure 4-8. Distribution of the Elevation (m) of the Template 2 and Template 3 Vehicles

Figure 4-9 shows the distribution of the data collection as a function of the difference between the minimum and the maximum elevation within each blob. To the extent that most of the 10-minute blobs were driven at highway speeds, this difference is a measure of the slope of the road on which tractors operated within each blob, indicating whether the vehicles were operated in flat or mountainous terrain. Based on Figure 4-9, it can be concluded that the T3 dedicated routes were over more mountainous terrain than the non-dedicated routes.

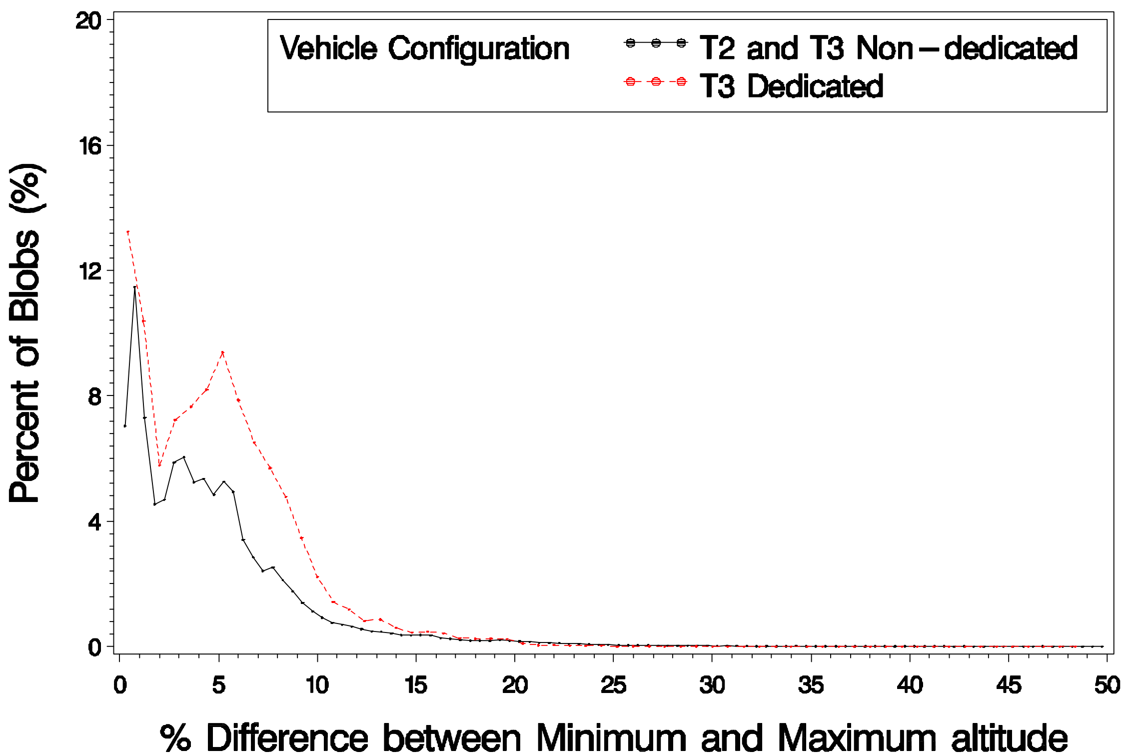


Figure 4-9. Percent of Blobs as a Function of the Difference between the Minimum and Maximum Elevation within Each Blob

<u>Longitudinal Acceleration</u>

Figure 4-10 illustrates the distribution of the minimum longitudinal acceleration of the tractors as a function of configuration and phase. For this analysis, Phases 1 and 2 data were defined by the generic Phase 2. As described in section 4.1, the generic Phase 2 period started when the driver training was conducted and technologies were first activated or radar was aligned by Meritor WABCO. Minimum longitudinal acceleration during a 10-minute blob represented the maximum deceleration (or braking) observed over that period. As such, Figure 4-10 provides information on the braking requirements during FOT driving by configurations and phases. These statistics were produced over the 10-minute blob period. If the statistics were produced on a 10-Hz basis, all the distributions would shift and contract to the right (less deceleration) due to the maximum that was taken over the 10-minute blob period. Thus, these profiles should not be interpreted to indicate that deceleration is occurring most of the time. Before identification of the minimum acceleration within each blob, a 5-point moving average was taken to address the noise observed in this sensor measurement. Additionally, a number of longitudinal accelerometers failed during the course of the study. The validation flags constructed when the data were loaded into the FOT analysis database were used to screen out as much of the data to the degree possible.

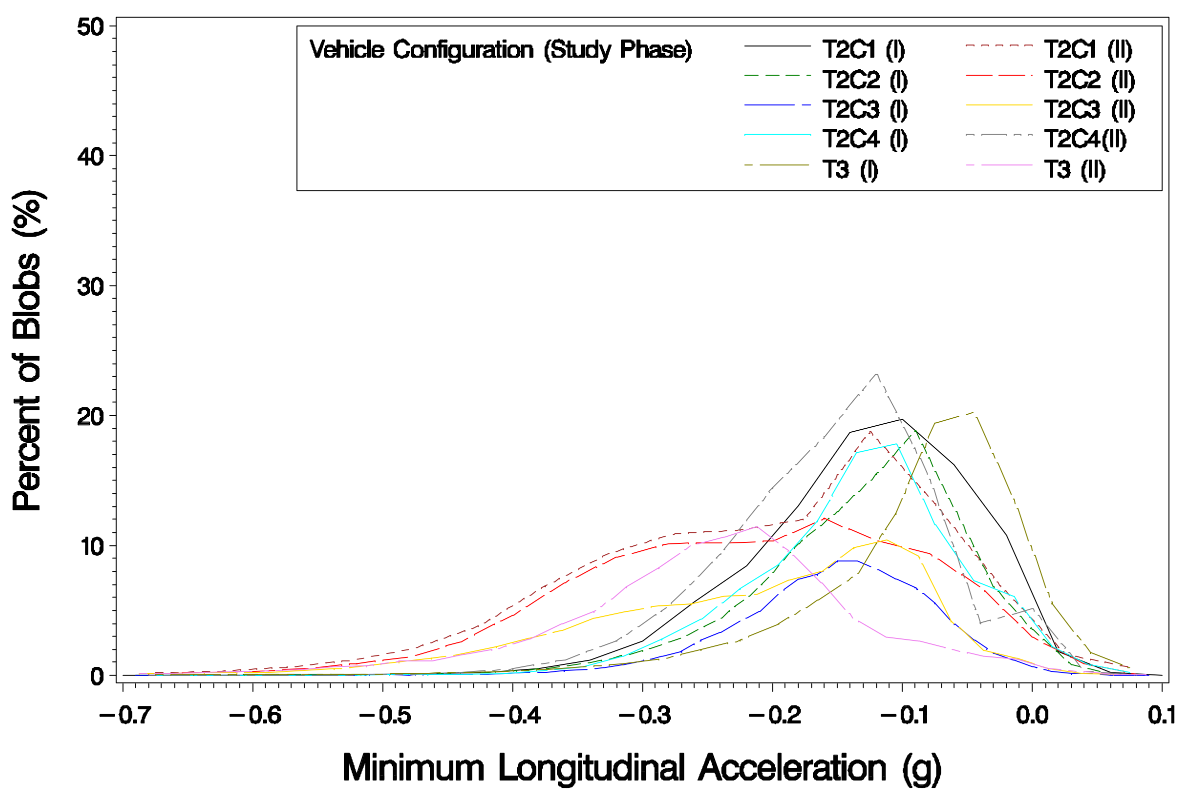


Figure 4-10. Distribution of Minimum Longitudinal Acceleration (g) within Each Blob

<u>Yaw Rate</u>

Figure 4-11 illustrates the distribution of the yaw rate of the tractors as a function of configuration and phase for the validation range utilized. For this analysis, Phase 1 and 2 data were defined by the generic Phase 2. As described in section 4.1, the generic phase 2 period started when the driver training was conducted and technologies were first activated or radar was aligned by Meritor WABCO. A number of yaw rate sensors also failed during the course of the study; validation flags were used to screen out these data from the analysis. A 5-point moving average was also used to smooth the yaw rate data prior to summarizing, because the raw data were observed to be noisy. As with the deceleration analysis, Figure 4-11 represents a summary of behavior across blobs. In this case, since the average yaw rate across blobs is depicted, the distribution of yaw rate on a 10-Hz basis would be considerably more spread out. For reference, on Figure 4-11, a tractor traveling at 55 mph traversing a 1000 ft radius of curvature curve would exhibit a yaw rate of approximately 4.6 deg/s.

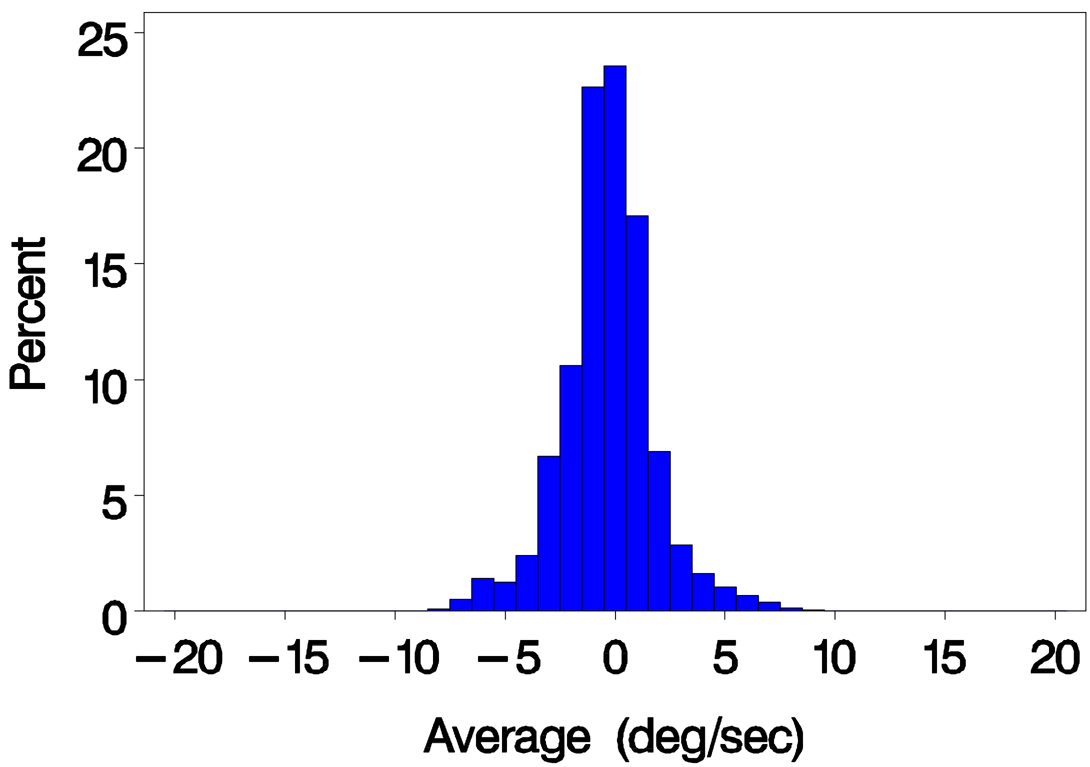


Figure 4-11. Distribution of Average Yaw Rate (deg/sec) within Each Blob

Target Range and Forward Vehicle Speed

Figures 4-12 and 4-13 illustrate the distribution of the average target range and forward lead vehicle speed across all blobs with average speed equal or greater than 20 mph. A target is present in 84 percent of the blobs collected. Blobs with no target are not included in this analysis. Approximately 20 percent of the blobs report a range of 0 feet. Because the statistics analyzed in these plots represent averages over 10-minute blobs, it is possible that these zero distance radar returns actually occurred during a portion of a blob when the truck was stopped. It is also possible that these zero distance targets occurred very briefly within blobs in which no other targets were detected, indicating that an additional 20 percent of blobs actually had no targets. The majority of the stopped lead vehicles depicted in Figure 4-13 likely correspond to the zero distance artifacts observed in Figure 4-12. Figure 4-12 indicates that approximately 250 feet is a common following distance for FOT tractors and that the speed profile of lead vehicles predominantly includes driving between 55 and 80 mph.

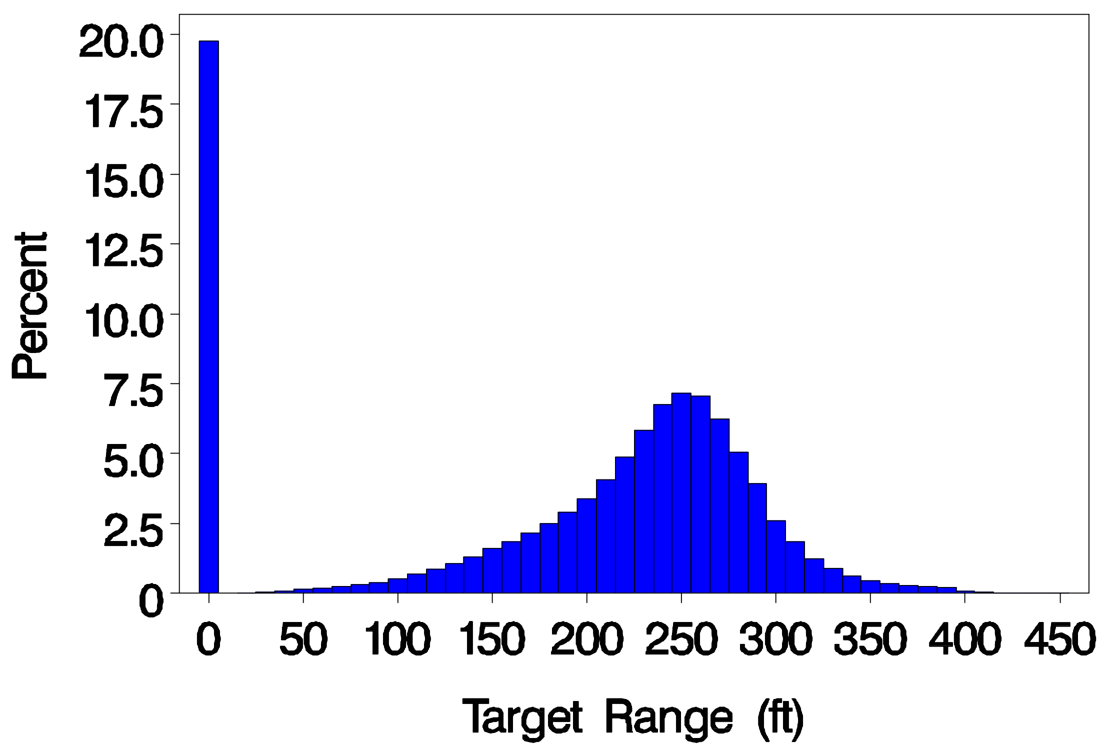


Figure 4-12. Distribution of Target Range (feet) within Each Blob

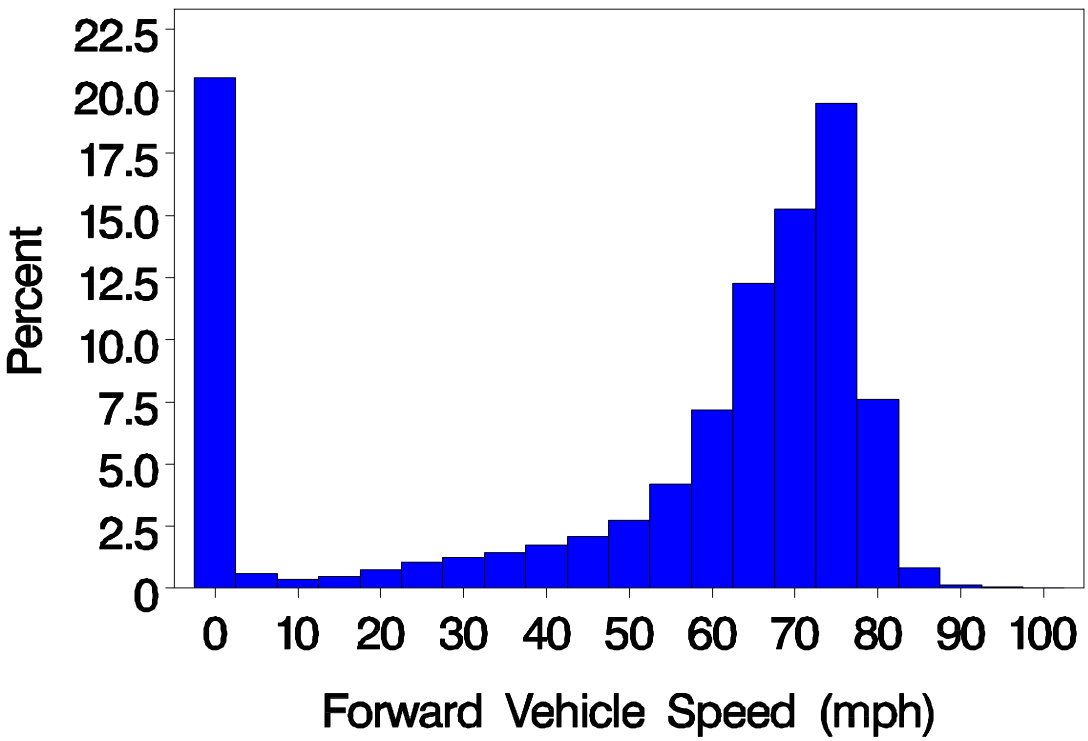


Figure 4-13. Distribution of Forward Vehicle Speed (mph) within Each Blob

4.4 Additional Onboard Data Characterization

For illustration purposes, this section presents data and associated histograms generated using a subset of 10-Hz data extracted from the database and decompressed to further characterize the data collected onboard the vehicles. The data selected were July 2005 and June 2006[6] data for one individual Template 3 tractor. The July 2005 data represent Phase 1 driving, while the June 2006 data represent Phase 2 driving.

[6] The decommissioning of the instrumentation was scheduled to occur within the months following the official end of the FOT, i.e. on May 1, 2006. Although the data collection period was officially terminated on April 30, 2006, some vehicles continued to collect onboard data until the DAS unit and other instrumentation hardware were removed.

Figure 4-14 shows the percent of time data were collected onboard this tractor from a Template 3 trailer, hence the percent of time data collected from a matched and optimized tractor-trailer. During July 2005, this particular T3 tractor exhibited a better than average (~43 percent) percentage of driving in the optimized configuration.

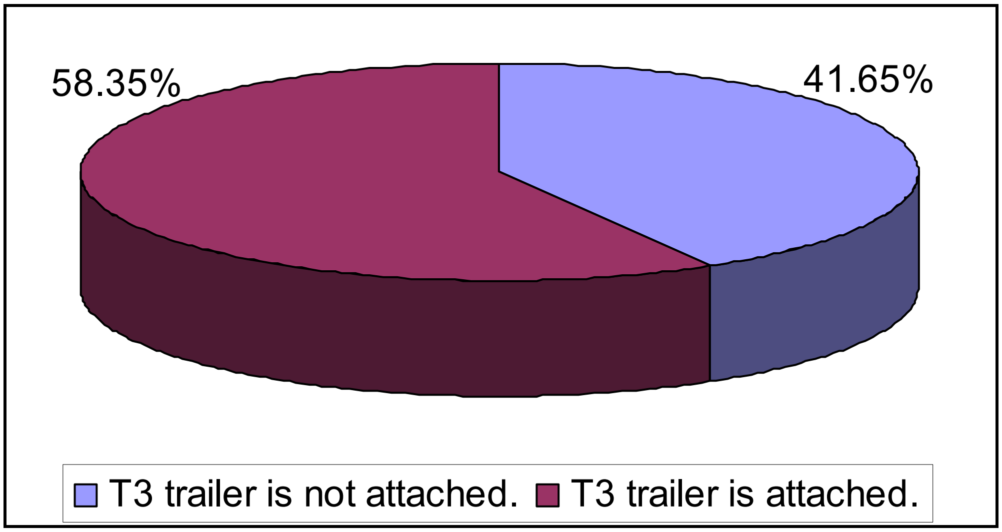


Figure 4-14. Data Collected Onboard the Tractor in Optimized and Non-Optimized Template 3 Configurations(July 2005)

Figure 4-15 illustrates the route driven by the tractor in July 2005: this Template 3 tractor drove from Loveland to Grand Junction, Colorado, on a dedicated route. Figure 4-16 shows a histogram of the vehicle speed.

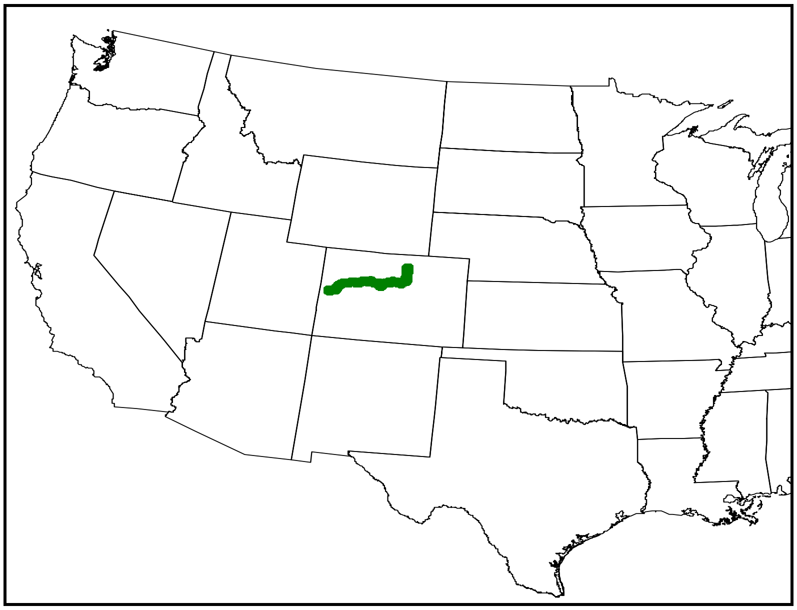


Figure 4-15. Route Driven by the Selected Template 3 Tractor in July 2005

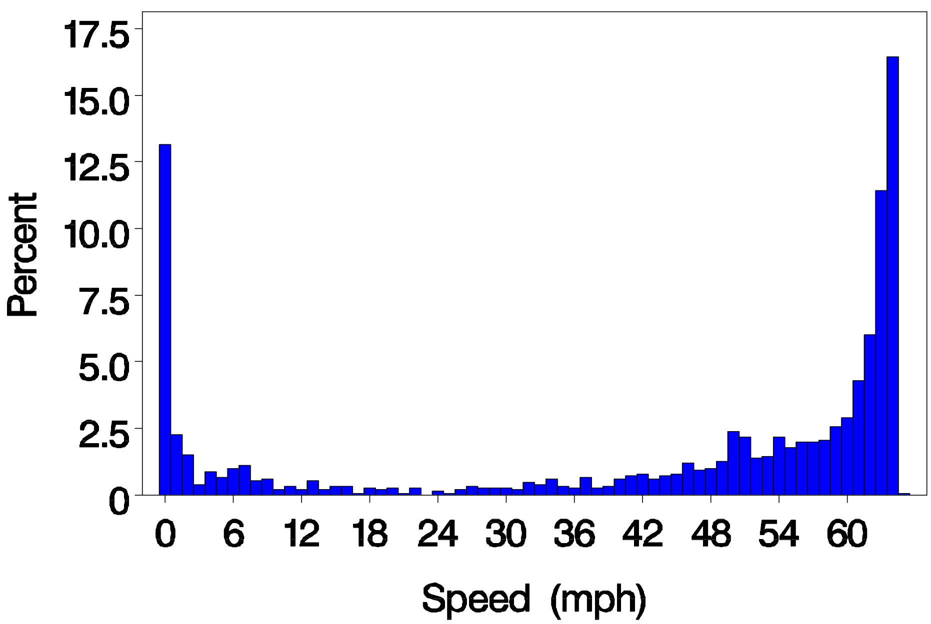


Figure 4-16. Distribution of the Selected Template 3 Tractor Speed (mph) in July 2005

For this tractor, Figure 4-17 illustrates the distribution of the maximum lateral accelerations within each blob (top plot) and average lateral accelerations within each blob (bottom plot) in July 2005.

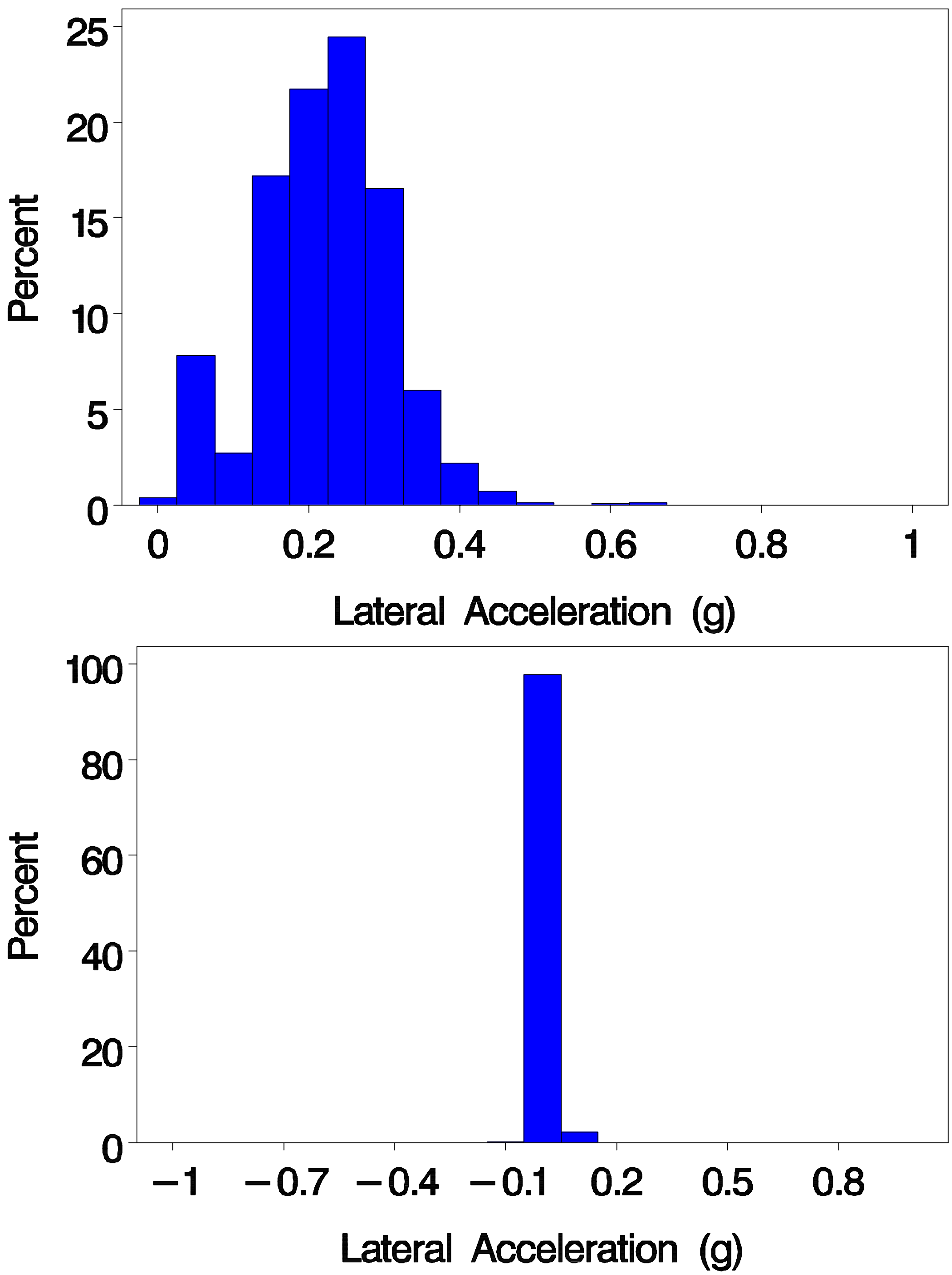


Figure 4-17. Distribution of the Maximum (top) and Average (bottom) Lateral Acceleration (g) of the Selected Template 3 Tractor in July 2005

As expected over a 10-minute period, average lateral acceleration is centered about zero with low variability. The distribution of maximum lateral accelerations over 10-minute periods indicates that, in most 10-minute intervals, a lateral acceleration of 0.2g or greater is observed. These minimum and average values are calculated based on data that have been smoothed with a 5-point moving average to address noise in the raw sensor data.

Figure 4-18 illustrates the distribution of the minimum longitudinal acceleration of the vehicle. The distribution of minimum longitudinal acceleration indicates that significant braking events (greater than 0.25g) occur in only a small fraction of 10-minute intervals. This is as expected. To carefully investigate performance of ECBS in hard braking situations, only blobs with the smallest minimal longitudinal accelerations need to be analyzed. The summary statistics, calculated for each blob and provided to the IE, identify these most relevant data.

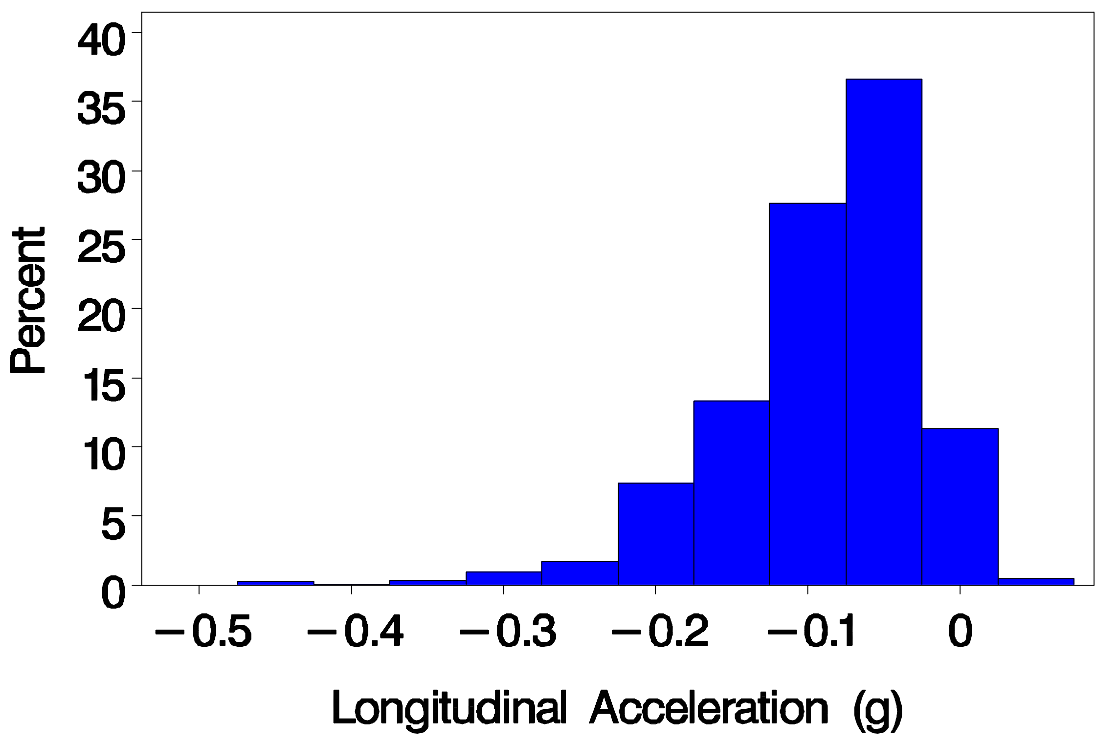


Figure 4-18. Distribution of Minimum Longitudinal Acceleration (g) in July 2005

Brake pressure data collected at each wheel were also characterized for the selected Template 3 tractor during the month of July 2005. The data trend that follows displays pressures for only one of the brake pressure channels, because all brake pressures responded similarly. Figure 4-19 shows the tractor front brake pressure as a function of the trailer pulled. When a Template 3 trailer is not attached, the tractor may be operating as a bobtail, pulling a trailer other than a Template 3 trailer, or pulling a Template 3 trailer without the second cable connected. This figure shows that the brakes are not applied for approximately 97 percent of the time.

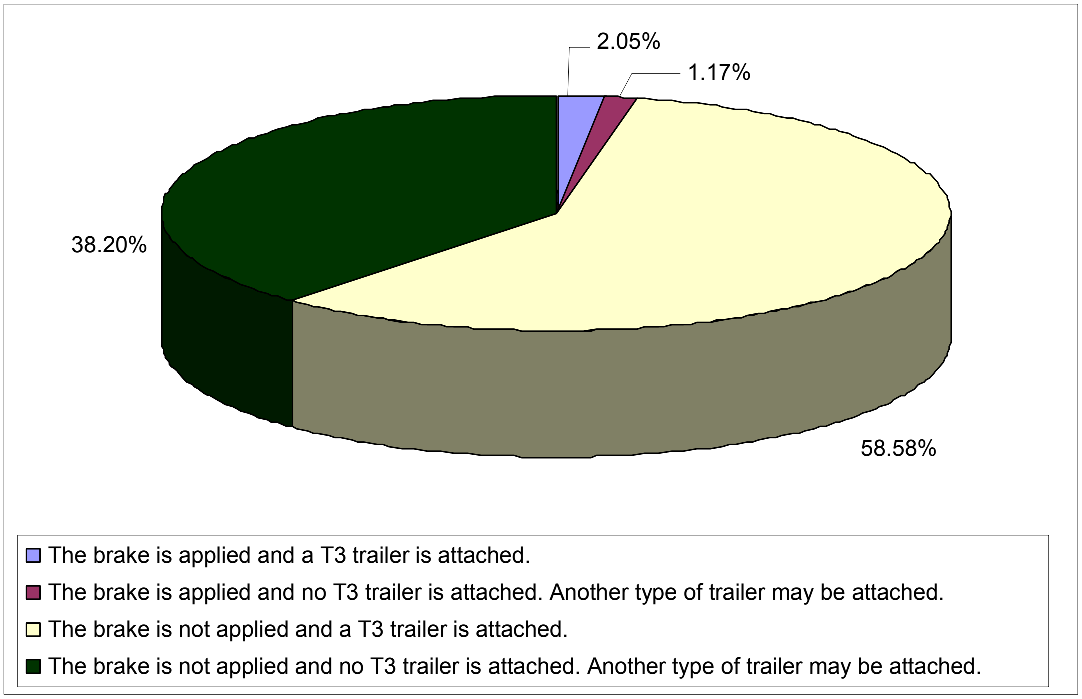


Figure 4-19. Distribution of Tractor Front Roadside Brake Pressure

Figure 4-20 illustrates the distribution of the front brake chamber pressure for the month of July 2005; the brake is not applied at the wheel for nearly 97 percent of the time, and pressure at the wheel is greater than 50 psi for only 0.023 percent of the time.

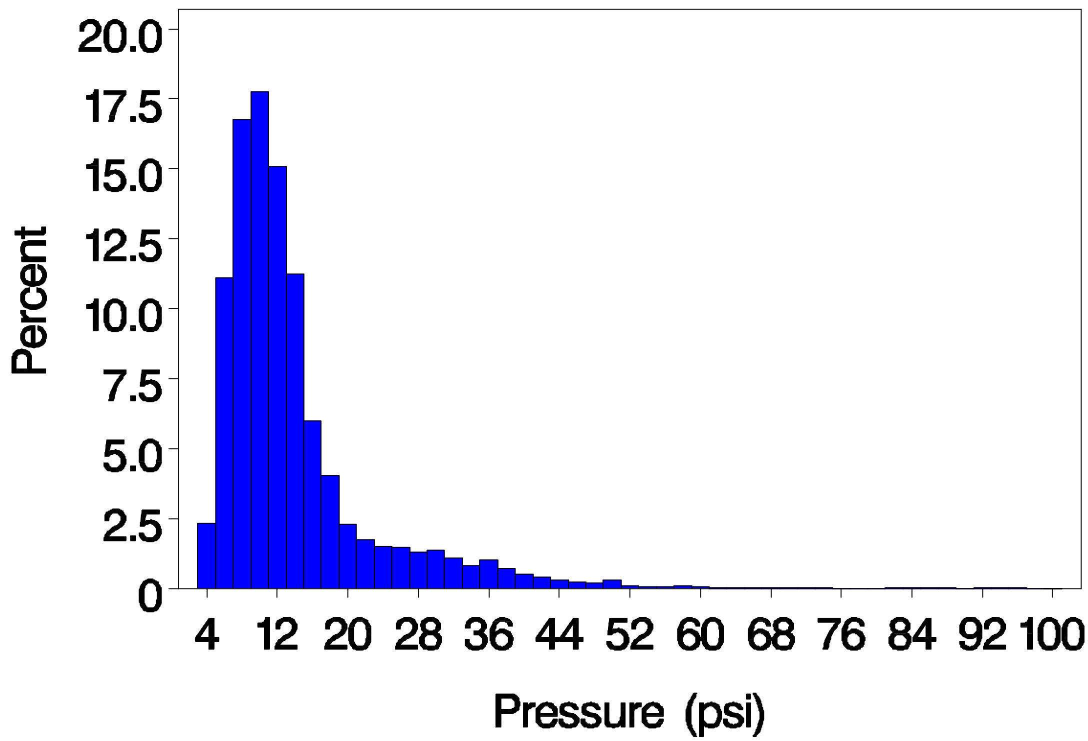


Figure 4-20. Brake Pressure Distribution (front roadside brake) in July 2005

Figure 4-21 shows the same brake pressure distribution as function of the trailer: with a Template 3 trailer (top) and without a Template 3 trailer (bottom). Based on Figure 4-21, it can be noted that higher pressures are observed (longer tail distribution) when a T3 trailer is attached[7].

[7] T3 drivers have reported that, when driving an optimized ECBS configuration tractor-trailer, they are more confident in their braking ability.

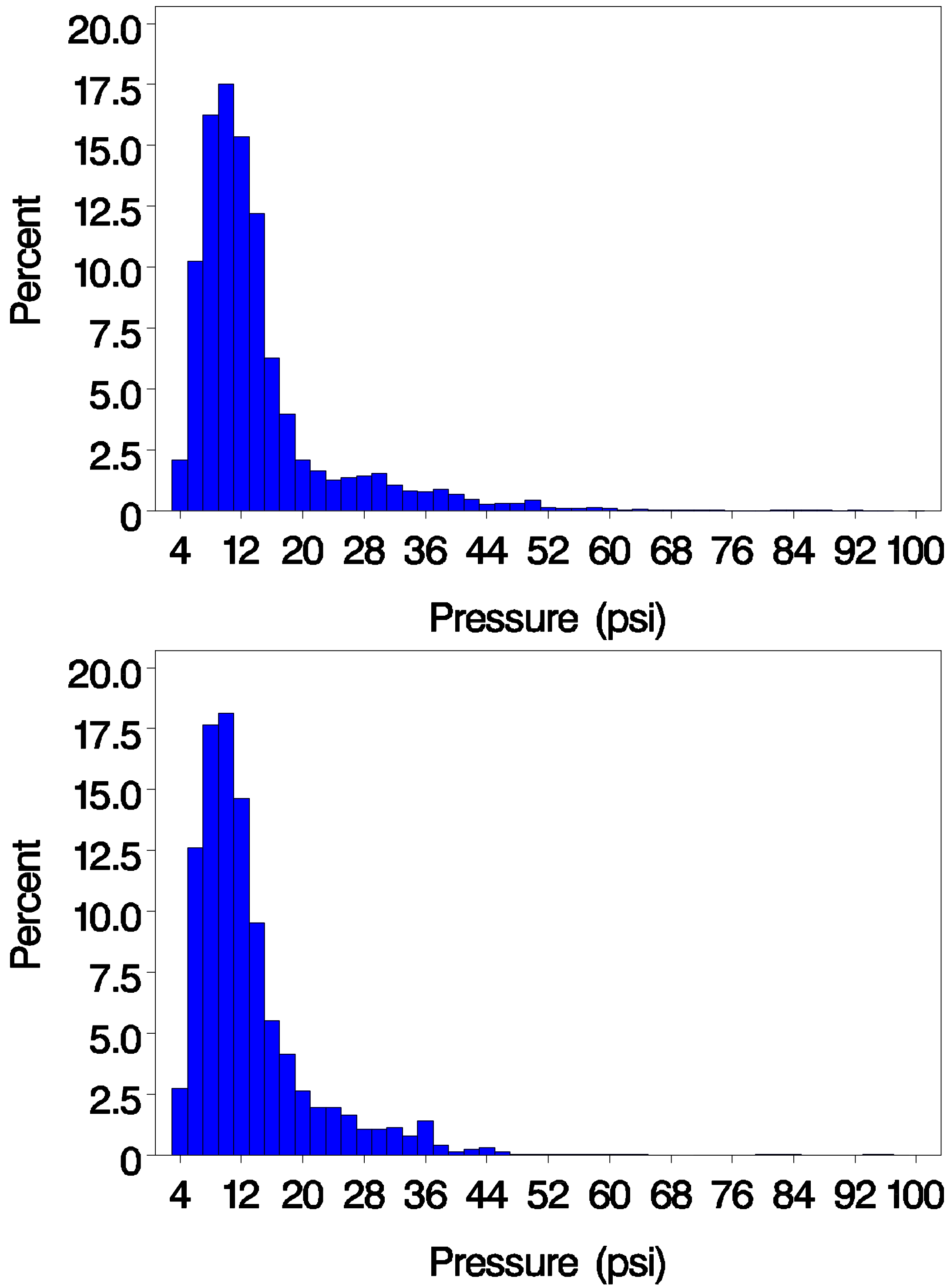


Figure 4-21. Brake Pressure Distribution (front roadside brake) in July 2005 With (top) or Without (bottom) a Template 3 Trailer

Figure 4-22 shows the percentage of time that the trailer front roadside brake pressure is greater than zero, and Figure 4-23 illustrates the distribution of the trailer front roadside brake pressure when it is greater than zero. Consistent with tractor brake pressure data, the trailer brakes are not applied for approximately 97 percent of the time.

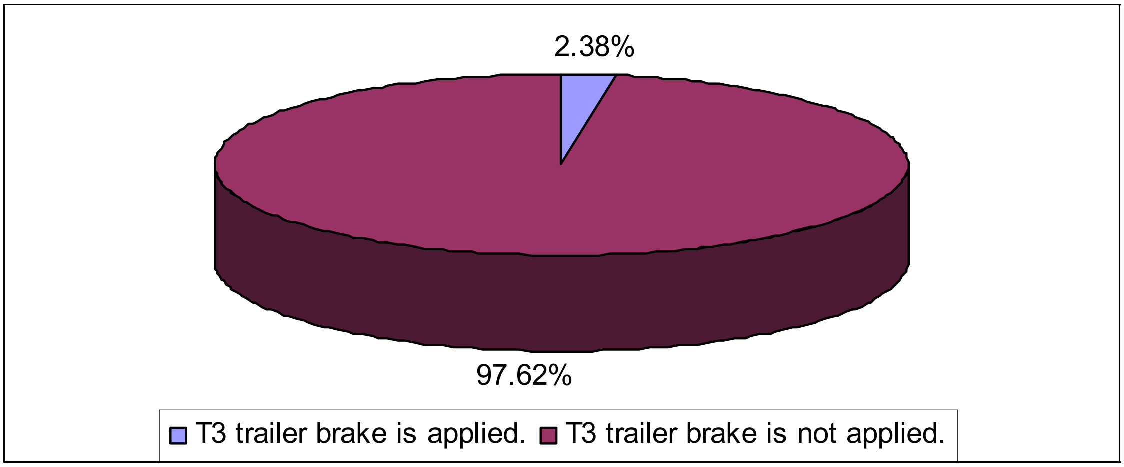


Figure 4-22. Distribution of the Trailer Front Roadside Brake Pressure

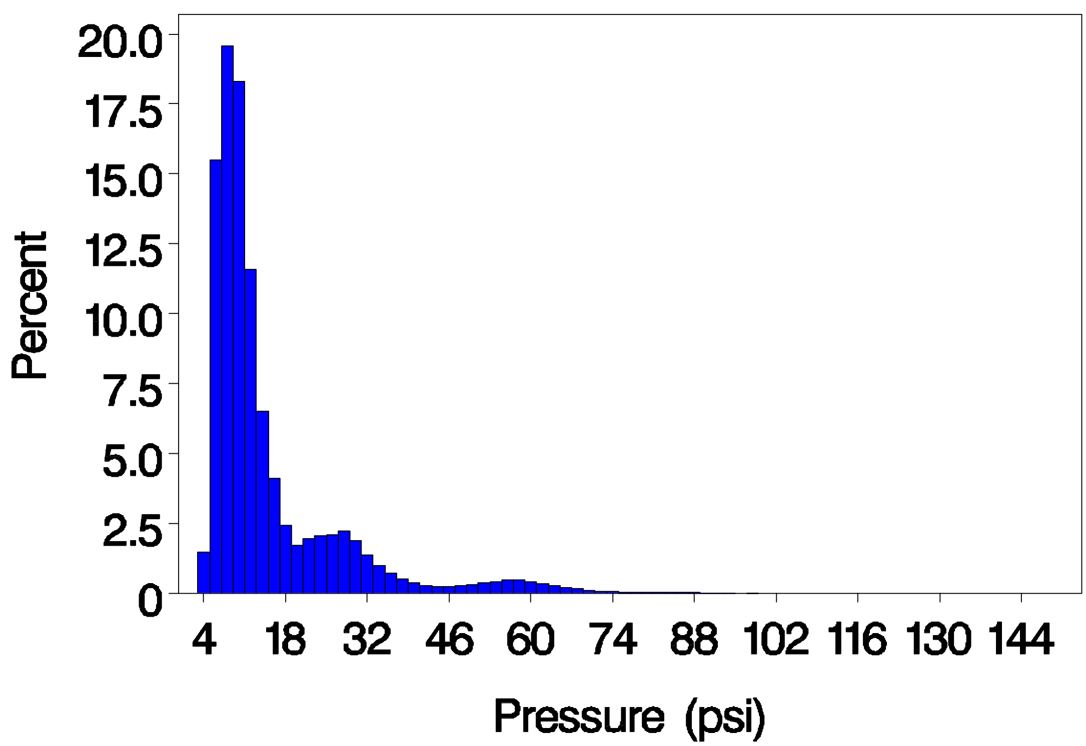


Figure 4-23. Brake Pressure Distribution (trailer front roadside brake) in July 2005

The distribution of trailer brake pressure depicted in Figure 4-23 appears to be multi-modal, with peaks at approximately 10, 28, and 58 psi. In-depth analysis of individual braking events would be required to fully understand why this behavior is observed. Such analyses are beyond the scope of the FOT conductor team's work. Analysis of additional trucks might indicate that this was merely a characteristic of the braking behavior of this individual truck driver.

Figure 4-24 illustrates the distribution of the CCC usage by blob of the Template 3 tractor in July 2005. This tractor had over 35 percent of its blobs with no cruise control usage and about 10 percent of its blobs with constant usage.

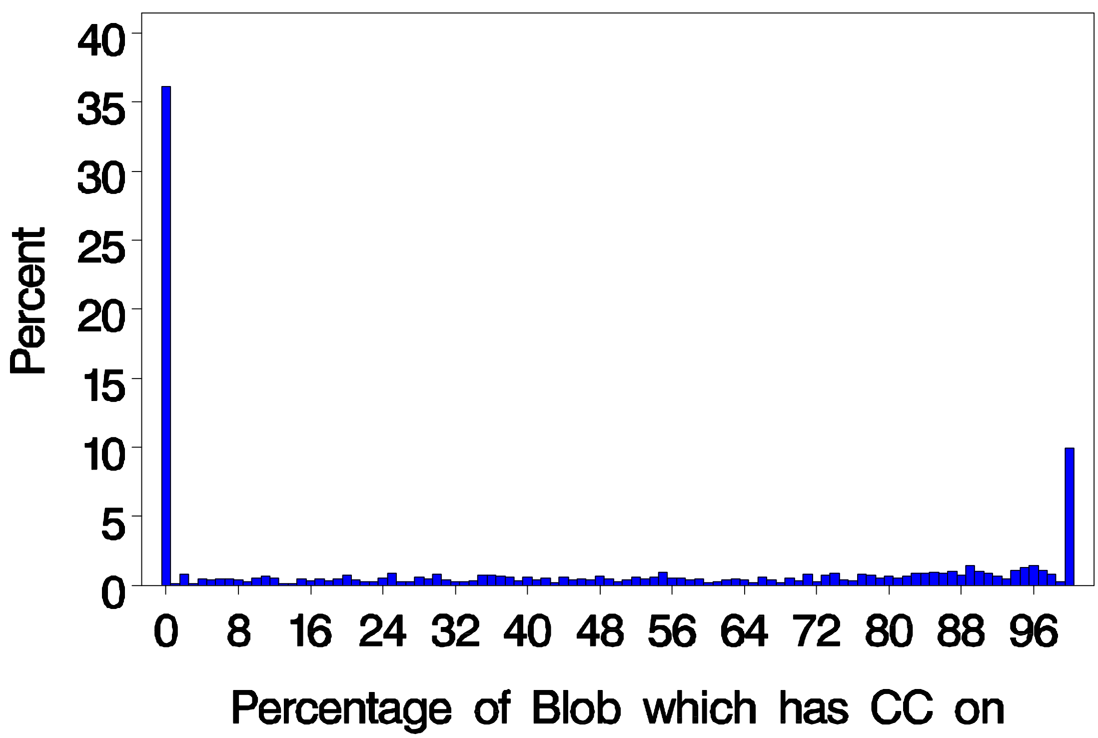


Figure 4-24. Distribution of the Conventional Cruise Control use as a Function of Speed (ft/s) for the Selected Template 3 Tractor in July 2005

To investigate the use of ACC for the same Template 3 tractor, data were extracted from the database for the month of June 2006. Summary statistics showed that:

- The ACC was off for a third of the driving time (33.76 percent)
- The ACC was on and active with:
  - Speed control for the majority of the time (63.34 percent)
  - Distance control for only 0.56 percent of the time
  - In overtake mode for 0.20 percent of the time
- The ACC was disabled or in error condition for 2.15 percent of the time.

Summary statistics from this vehicle in June 2006 showed that the driver conventional cruise control was ON for only 0.70 percent of the time.

Figure 4-25 shows the speed distribution of the Template 3 vehicle for the ACC on and off. Clearly, ACC is being used predominantly at highway speeds (~ 65 mph), and most of the driving at highway speed is done with ACC on.

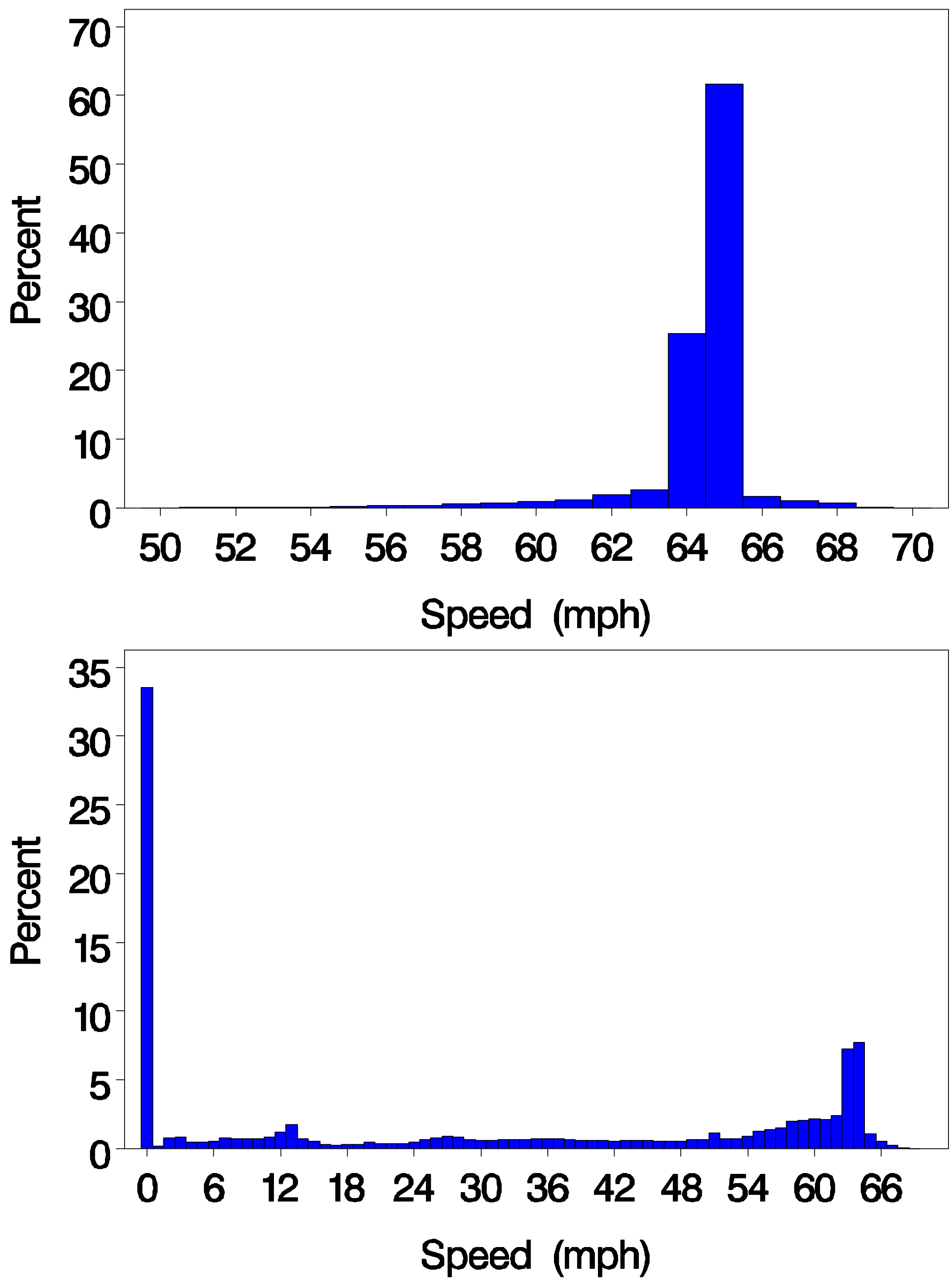


Figure 4-25. Distribution of the Vehicle Speed for the Selected Template 3 Tractor in June 2006 when ACC was ON (top) and OFF (bottom)

Figure note: The ACC was On at Speeds below 50 mph for 0.15 Percent of the Time

Using the decompressed data, the Freightliner Team applied predefined trigger algorithms to identify situations of interest, e.g., driving situations that may or may not result in crashes. The triggers defined for video data triggering (Table 3-8) were applied as a preliminary investigation to the May 2005 data extracted for the selected Template 3 tractor. Table 4-9 lists the number of times the conditions defined by each trigger were met. This tractor drove 10,973 miles during this time.

Table 4-9. Identification of Situations where Trigger Conditions are Met (May 2005)

Conditions for Trigger	Number of Occurrences
Steer angle >120deg and speed>20 mph	50
Longitudinal Acceleration< -0.31g and Brake pedal pressure>0psi	19
Lateral Acceleration>0.35g and speed>20 mph	198
ABS activation (ABS='01')	8
Brake pedal pressure>75psi and speed>20 mph	3
Wheel speed difference >7 mph	0
Yaw rate>30deg/s and speed>20mph	0
Steer angle >120deg and speed>20mph	50

All parameters except ABS Activation were smoothed using a 0.5 second moving average

4.5 Survey Data

Surveys of drivers and technicians involved in the FOT were conducted before exposure to the Freightliner tractors with ECBS, ABS6, and/or disc brakes (Phase 1), before exposure to the enabled technologies (Phase 2), and after exposure to the enabled technologies (Phase 2).

Table 4-10 summarizes the response rates at each stage of the data collection, for technicians and drivers. Several technicians and drivers responded to more than one survey. All detailed information, with coded, completed surveys, was sent to the IE shortly after receipt of completed surveys from the respondents.

Table 4-10. Technician and Driver Surveys Completed

Participants		Baseline, Before Phase 1	After Phase 1, Before Phase 2	Final, After Phase 2
Technicians	n/a	34	16	20
Drivers	T2C1	2	1	7
	T2C2	1	4	9
	T2C3	1	5	4
	T2C4	0	3	8
	Template 2 Total	4	13	28
	Template 3	8	3	8
	Total	12	16	36

Analysis of the survey responses is outside the scope of this report.

4.6 Maintenance and Inspection Data

Maintenance data in the form of printed ROs (example shown in Figure 4-26) were obtained in two batches, as listed in Table 4-11. Note that maintenance records prior to the start of the data collection (May 1, 2005) and after completion of the data collection (April 30, 2006) were obtained, hence increasing the amount of data collected for the analysis.

Repair Order

Facility	Company	
006719 - Loveland, CO 7500 1/2 E. Crossroads Blvd. Loveland CO 80537	Region B *Fleet* 006819 - Loveland.CO *EqType* Tractor *Unit* Wal*Mart Vehicle ID	RO Code *Status* Closed

Reason For Repair **04** *RO Contains DVCR?* **No** *RO Red Tag Status* **Not Red Tagged**

Year / Make / Model	*VIN*	*License Plate*	*RO Date*
2004 FRGHT FL120	Wal*Mart Vehicle VIN	License Plate number	RO DATE
1st Meter Reading	*2nd Meter Reading*	*License State/Province*	
1,736 Odometer Miles		**Oklahoma**	

Line	*Reason For Repair*	*SJ Code*	*Service Index*
1	**04 — Driver's Report**		
Status **C**	*Problem Description* **on air to trailer brakes ice in gladhand driver didn't hang up lines**		
	Repair Line DVCR? **No** *Repair Line Red Tag* **Not Red Tagged**		

	Cost Center	GL Account
Labor	006709 Power Equipment (6106254)	Associate Wages (0911)
Part	006709 Power Equipment (6106254)	Tractor Parts (1045)
Outside Labor	006709 Power Equipment (6106254)	Truck Repair & Maintnenance (0957)
Outside Part	006709 Power Equipment (6106254)	Truck Repair & Maintnenance (0957)

Labor

Emp	*In/Outside*	*Date*	*PO#*	*Sys/Assy / Work Accomplished / Tech Remarks*	*Regular*	*OT*	*Labor Cost*
Wal*Mart Technician		RO DATE		013/010 Brakes/Air Type Power Brakes (See 24 Repair removed ice from air lines	1.17	0.00	26.91

Parts

Inv Site	*In/Outside*	*PO #*	*Part #*	*Sys/Assy/Part*	*Description*	*Qty*	*Total*

Fluid

Inv Site	*In/Outside*	*PO #*	*Part #*	*Description*	*Qty*	*Total*

Outside Repair

Date	*PO #*	*Vendor #*	*Vendor Name*

Outside Repair Summary

Date	*PO #*	*Vendor #*	*Vendor Name*	*Labor*	*Part Cost*	*Misc Cost*	*Shipping*	*Sales Tax*	*Total Cost*

RO Notes	*Signature*	*Date*

Figure 4-26. Example of a Repair Order Generated during the FOT

Figure note: Vehicle and Technician Information have been Removed for Insertion in the Report

Table 4-11. Maintenance Records

	Batch 1	Batch 2
Dates	December 1, 2004 to December 1, 2005	December 1, 2005 to September 30, 2006
Tractor repair orders	314	TBD
Brake-related	106	TBD
Tire-related	208	TBD
Trailer repair orders	94	TBD
Brake-related	38	TBD
Tire-related	56	TBD
Total	408	TBD

Brake system inspections were conducted in October 2006 on a subset of tractors and trailers, as described in Table 4-12. The tractor mileages exceeded 250,000 miles at the time of inspections. Trailer mileages were not available: the trailers were not equipped with axle/hub odometers, and Wal★Mart does not track mileage separately. Wear data for the shoes/drums and pads/discs were measured by Bendix representatives and were provided to the IE.

Table 4-12. Brake System Inspections

	Inspections #
Tractors	12
Disc brakes	6
Drum brakes	6
Trailers	4
Disc brakes	2
Drum brakes	2
Total	16

5.0 CLOSING REMARKS

The research program benefited the trucking industry and the general public by advancing technologies that have a potential to enhance safety on our nation's highways. Substantial field data and experience were obtained on performance, reliability, maintainability, durability, compatibility, and safety of ECBS, ECBS-enabled technologies, and ADB in real-world environments:

- Forty-eight (48) tractors and one hundred (100) trailers were outfitted with various combinations of standard production and preproduction brake and safety systems including ECBS, next-generation ABS, ACC, roll stability technologies, yaw stability technologies, and ADB
- The tractors and trailers were successfully fielded for 12 months in a normal operating environment
- ECBS, enabled technologies, and ADB integrated on the tractors and trailers functioned with no major interruption or failure in several million miles and nearly 2 years of service,
- Technologies were activated in stages during the data collection period, and the enabled technologies were implemented successfully
- No incompatibility of advanced technology tractors or trailers with conventional tractors and trailers were observed in several million miles and nearly 2 years of service
- Over 4 million miles of engineering data were collected onboard the tractors and trailers
- Maintenance operations of the fleet were recorded on the tractors and trailers for the duration of the FOT, i.e. from the date the vehicles were placed in service to the end of data collection, totaling 22 months of operation
- Opinions of 34 technicians and 40 drivers were obtained
- The Wal★Mart fleet, its drivers, and mechanics reported being satisfied with the performance of the tractors and trailers.

6.0 REFERENCES

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USDOT 2003. "Field Operational Test of Electronically Controlled Braking Systems (ECBS); Template 2: Mixed Tractor-Trailer FOT; Template 3: Optimized Tractor-Trailer FOT," Cooperative Agreement DTFH61-02-X-00096 Between Freightliner LLC, and U.S. DOT, Federal Highway Administration, May 1, 2003.