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Medium Truck Duty Cycle Data from Real-World Driving Environments: Project Final Report

November 1, 2012

Prepared by
Mary Beth Lascurain, Oscar Franzese, Gary Capps, Adam Siekmann, Neil Thomas, Tim LaClair, Alan Barker, Helmut Knee

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ORNL/TM-2012/240

Vehicle Systems Program

MEDIUM TRUCK DUTY CYCLE DATA FROM REAL-WORLD DRIVING ENVIRONMENTS: PROJECT FINAL REPORT

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ACRONYMS AND ABBREVIATIONS

ASCII	American Standard Code for Information Interchange
CAN	Controller Area Network
CMV	Commercial Motor Vehicle
CSV	comma-separated value
CTA	Center for Transportation Analysis
Dana	Dana Corporation
DAS	data acquisition system
DASIB	data acquisition system interface box
DBAU	Data Bus Analysis Utility
DOE	US Department of Energy
DOT	US Department of Transportation
DCGenT	Duty Cycle Generation Tool
EOBR	electronic onboard recorder
EPA	Environmental Protection Agency
FCWS	Fountain City Wrecker Service
FE	fuel efficiency
FOT	Field Operational Test
FMCSA	Federal Motor Carrier Safety Administration
GB	Gigabyte
GIS	geographic information system
GPS	global positioning system
GUI	graphical user interface
GVW	gross vehicle weight
HTDC	Heavy Truck Duty Cycle
HTH	H. T. Hackney Company
KAT	Knoxville Area Transit
KUB	Knoxville Utilities Board
MARC	Michelin Americas Research and Development Corp.
MOA	Memorandum of Agreement
MOE	measure of effectiveness
MTDC	Medium Truck Duty Cycle
NGWBSTs	New-Generation Wide-Based Single Tires
NTRC	National Transportation Research Center
ORNL	Oak Ridge National Laboratory
PTO	power takeoff
PSAT	Powertrain Systems Analysis Toolkit
SAE	Society of Automotive Engineers
SDMS	Safety Data Message Set
SIE	file extension descriptor assigned by HBM/SoMat
SIF	SoMat information file
TAMS	Transportation Analysis, Modeling, and Simulation
THP	Tennessee Highway Patrol
TPMS	Tire Pressure Monitoring System
UTC	universal time coordinates / Universal Coordinated Time
vehicle	test vehicle, including tractor and/or trailer unit(s)
VIUS	Vehicle Inventory and Use Survey
WRI	Wireless Roadside Inspection
21CTP	21st Century Truck Partnership

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We would also like to thank the Federal Motor Carrier Safety Administration for making possible the collection of additional safety-related signals through its funding for the associated sensors; MGM Brakes for the installation cost of the e-Stroke units; and the Tennessee Highway Patrol of the Tennessee Department of Safety and Homeland Security for providing manpower to assist in the calibration of the onboard self-weighing units.

Finally, the project team would like to thank Lee Slezak (DOE Office of Vehicle Technologies) for his continued support of this important project. His encouragement, guidance, and enthusiasm for this work, along with the financial support for its conduct, were the foundation that allowed this project to be conducted. We are indebted to him for his support.

EXECUTIVE SUMMARY

Since the early part of the 20th century, the US trucking industry has provided a safe and economical means of moving commodities across the country. At present, nearly 80% of US domestic freight movement involves the use of trucks. The US Department of Energy (DOE) is spearheading a number of research efforts to improve heavy vehicle fuel efficiencies. This includes research in engine technologies (including hybrid and fuel cell technologies), lightweight materials, advanced fuels, and parasitic loss reductions. In addition, DOE is developing advanced tools and models to support heavy vehicle research and is leading the 21st Century Truck Partnership and the SuperTruck development effort. Both of these efforts have the common goal of decreasing the fuel consumption of heavy vehicles. In the case of SuperTruck, a goal of improving the overall freight efficiency of a combination tractor-trailer has been established.

This Medium Truck Duty Cycle (MTDC) project is a critical element in DOE's vision for improved heavy vehicle energy efficiency; it is unique in that there is no other existing national database of characteristic duty cycles for medium trucks based on collecting data from Class 6 and 7 vehicles. It involves the collection of real-world data on medium trucks for various situational characteristics (e.g., rural/urban, freeway/arterial, congested/free-flowing, good/bad weather) and looks at the unique nature of medium trucks' drive cycles (stop-and-go delivery, power takeoff, idle time, short-radius trips). This research provides a rich source of data that can contribute to the development of new tools for FE and modeling, provide DOE a sound basis upon which to make technology investment decisions, and provide a national archive of real-world-based medium-truck operational data to support energy efficiency research. The MTDC project involved a two-part field operational test (FOT). For the Part-1 FOT, three vehicles each from two vocations (urban transit and dry-box delivery) were instrumented for the collection of one year of operational data. The Part-2 FOT involved the towing and recovery and utility vocations for a second year of data collection.

The vehicles that participated in the MTDC project did so through gratis partnerships in return for early access to the results of this study. Partnerships such as these are critical to FOTs in which real-world data is being collected. In Part 1 of the project, Oak Ridge National Laboratory (ORNL) established partnerships with the H.T. Hackney Company (HTH), one of the largest wholesale distributors in the country, distributing products to 21 states; and with Knoxville Area Transit (KAT), the city of Knoxville's transit system, which operates across Knoxville and parts of Knox County. These partnerships and agreements provided ORNL access to three Class-7 day-cab tractors that regularly haul 28 ft pup trailers (HTH) and three Class-7 buses for the collection of duty cycle data. In addition, ORNL collaborated with the Federal Motor Carrier Safety Administration (FMCSA) to determine if there were possible synergies between this duty cycle data collection effort and FMCSA's need to learn more about the operation and duty cycles of medium trucks. FMCSA's primary interest was in collecting safety data relative to the driver, carrier, and vehicle. In Part 2 of the project, ORNL partnered with the Knoxville Utilities Board, which made available three Class-8 trucks. Fountain City Wrecker Service was also a Part 2 partner, providing three Class-6 rollback trucks.

In order to collect the duty cycle and safety-related data, ORNL developed a data acquisition system (DAS) that was placed on each test vehicle. Each signal recorded in this FOT was collected by means of one of the instruments incorporated into each DAS. Other signals were obtained directly from the vehicle's J1939 and J1708 data buses. A VBOX II Lite collected information available from a global positioning system (GPS), including speed, acceleration, and spatial location information at a rate of 5 Hz for the Part 1 FOT. For the Part 2 FOT, this information was obtained from DAS-based GPS instrumentation. The Air-Weigh LoadMaxx, a self-weighing system that determines the vehicle's gross weight by means of pressure transducers, was used to collect vehicle payload information for the combination, urban transit, and towing and recovery vehicles. A cellular modem, the Raven X EVDO V4221, facilitated the communication between the eDAQ-lite (the data collection engine of the system) and the user. The modem functioned as a wireless gateway, allowing data retrievals and system checks to be performed remotely. Also, in partnership with FMCSA, two additional safety sensors were installed on the combination vehicles: the MGM e-Stroke brake monitoring system and the Tire SafeGuard tire pressure monitoring system. All of these sensors posted data to the J1939 data bus, enabling the signals to be read without any additional DAS interface hardware. Seventy-three signals from the various deployed sensors and from the available vehicle systems were collected. Because of the differences in vehicle data buses (J1939 and J1708), not all desired signals were available for all test vehicles.

ORNL developed a data-retrieval and archiving system that accessed the vehicles automatically over the air and downloaded the collected information resident on each onboard DAS. Each day the system emailed a summary of the data downloaded from each vehicle to the ORNL researchers, highlighting any sensors that showed a percentage of error above a predefined threshold.

Data collection began in May 2009 just prior to the official signing of the Memoranda of Agreement (MOAs) that took place at a ceremony held at the National Transportation Research Center (NTRC) in Knoxville, Tennessee, on July 7, 2009. During the two-part FOT, the 12 participating vehicles logged over 193,000 miles (45,400 for the combination trucks, 59,400 for the transit buses, 18,000 for the utility vehicles, and 70,000 for the towing and recovery trucks) and consumed over 30,000 gal of fuel (6,000 for the combination trucks,11,300 for the transit buses, 5,000 for the utility vehicles, and 8,000 for the towing and recovery trucks), while conducting business in the East Tennessee area.

For the combination trucks, the largest proportion of idling time and fuel consumed while idling corresponded to idling intervals lasting 0–5 min (i.e., intervals involving traffic congestion and delay at traffic signals). The transit buses also spent most of their idling time in congestion and bus dwelling stops (0–5 min idling interval). However, unlike the combination trucks, the transit buses spent about a fifth of their idling time in intervals longer than 4 h. In the case of the utility vehicles, the largest proportion of idling time and idling fuel consumed corresponded to idling intervals lasting 15–60 min. For the towing and recovery trucks, 5–15 min interval accounted for the largest percentage of idling time and fuel consumed while idling. The overall and moving fuel efficiencies ranged greatly across vocations, from as low as 3.6 mpg overall for the utility vehicles to 9.7 mpg at speed for the towing and recovery trucks.

One very important variable affecting the fuel efficiency of any vehicle is its payload level. The collected and post-processed data indicated that, on average, the combination trucks weighed 27,700–29,000 lb (GVW), the buses 23,000–23,800 lb, and the towing and recovery vehicles 17,000–33,000 lb. The utility vehicles were not instrumented with weight sensors since they do not experience significant variations in weight during their vocational activities. To generate the distribution of fuel efficiency under the payload levels described, 10 mile segments were considered for which the fuel efficiency was computed and counted as one observation. Overall, the fuel efficiency was found to decrease as the payload increased for the combination and the towing and recovery trucks, as expected. In the case of the transit buses, the relationship between fuel efficiency and vehicle weight was not as expected; rather, fuel efficiency tended to increase with increases in payload. This phenomenon is due to several factors, including idling while empty and having a larger number of passengers on highway routes.

The data collected in this project was also used to investigate two aspects of routing: (1) the variability that may exist in duty cycles that are generated by the same vocation and follow the same route; and (2) the effect of route optimization on fuel savings. The measures used in this analysis indicated that the highway duty cycles presented a higher variability than the surface-street duty cycles, a difference largely attributed to the variability in traffic conditions. In the majority of the cases studied, a duty cycle of the original sequence of stops with route optimization was found to be better than the original routing in both of the measures considered (including travel time and fuel savings); optimization of both routing and stop sequencing led to even better performance.

1. PROJECT OVERVIEW

Since the early part of the 20th century, the US trucking industry has provided a safe and economical means of moving commodities across the country. Now, in the early part of the 21st century, nearly 80% of US domestic freight movement involves the use of trucks. The 2002 Vehicle Inventory and Use Survey (VIUS, Department of Commerce, 2005) estimates that there are more than 3 million medium trucks (Class 3 through Class 7, between 10,001 and 33,000 lb gross vehicle weight [GVW] rating) registered in the United States. It is estimated that Class-6 and Class-7 commercial vehicles together consume in excess of 4 billion gal of fuel each year, second only to Class-8 tractor-trailers in the commercial truck sector.[1] Given the rising cost of fuel, increased effort should be placed on advanced technologies and new research and development efforts that will significantly contribute to enhanced fuel efficiency (FE) for heavy and medium trucks.

The US Department of Energy (DOE) is spearheading a number of research efforts to improve heavy vehicle FEs. This includes research in engine technologies (including hybrid and fuel cell technologies), lightweight materials, advanced fuels, and parasitic loss reductions. In addition, DOE is developing advanced tools and models to support heavy vehicle research and is leading the 21st Century Truck Partnership (21CTP)[2] and the SuperTruck development effort. These efforts have the common goal of decreasing the fuel consumption of heavy vehicles. In the case of SuperTruck, a goal of improving the overall freight efficiency of a combination tractor-trailer has been established.

This Medium Truck Duty Cycle (MTDC) Project is a critical element in DOE's vision for improved heavy vehicle energy efficiency. It involves the collection of real-world data for various situational characteristics (e.g., rural/urban, freeway/arterial, congested/free-flowing, good/bad weather) and looks at the unique nature of medium trucks' drive cycles (stop-and-go delivery, power takeoff [PTO], idle time, short-radius trips) to provide a rich source of data that can contribute to the development of new tools, to provide DOE a sound basis upon which to make technology investment decisions, and to provide a national archive of real-world-based medium-truck operational data to support vehicle energy efficiency research.

A quantitative profile of the driving behavior of medium trucks does not currently exist. A thorough understanding of the operation of medium trucks within duty cycles that reflect real-world conditions is an asset that would have great benefit to DOE, other federal agencies (e.g., the US Department of Transportation [DOT] and its interest in truck safety, the Environmental Protection Agency [EPA] and its interest in real-time emissions data), and the overall trucking industry (e.g., to better understand the means for improving FEs to contribute to improved profit margins).

1.1 PRIOR DUTY CYCLE EFFORTS

Oak Ridge National Laboratory's (ORNL's) Center for Transportation Analysis[3] (CTA) recently conducted the Heavy Truck Duty Cycle (HTDC) project for DOE which focused on the collection of duty cycle data relative to Class-8 vehicles.[4] The HTDC effort was conducted in three phases.

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[1] Based on estimates from the 2002 VIUS.

[2] http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/21centurytruck/.

[3] http://cta.ornl.gov/cta/ .

[4] Capps G., O. Franzese, B. Knee, M. B. Lascurain, and P. Otaduy, *Class-8 Heavy Truck Duty Cycle Project Final Report* (ORNL/TM-2008/122), 2008.

Phase 1 of the HTDC project was conducted from January 2005 through March 2006 and involved pilot testing of one instrumented Class-8 tractor-trailer, operating cross-country (east to west and north to south) while fully loaded. The purpose of the pilot testing was to design an appropriate data collection suite and to field-harden associated sensors, instrumentation, and a data acquisition system (DAS). The effort involved outfitting a truck with sensors and instrumentation to collect 104 channels of data over a 3 month time frame. The truck completed two east-west runs and two north-south runs. To leverage the resources required for pilot testing, a partnership was established with Dana Corporation (Dana) of Kalamazoo, Michigan, and Michelin Americas Research and Development Corporation (MARC) of Greenville, South Carolina. Both Dana and MARC were interested in collecting data for their own research from the pilot testing and provided in-kind resources (e.g., gratis usage of a Dana tractor and trailer and specialized test equipment). MARC's interest involved the field testing of its New-Generation Wide-Based Single Tires (NGWBSTs) and standard dual tires to assess any FE impacts. The pilot test involved alternating between standard dual tires and the NGWBSTs for the various runs. Over 50 gigabytes (GB) of data was collected during the pilot test.

Phase 2 of the HTDC project involved the design of a streamlined DAS and sensor suite that could withstand the rigors of being mounted on a commercial vehicle during its normal vocation, and would require no human interaction for initialization on vehicle startup at the beginning of each day or each route. Additionally, the number of major system components was reduced to four (DAS, vehicle self-weighing system, weather station, vehicle position and motion system). The resulting DAS was capable of collecting 60 channels of data and storing it internally in its dynamic memory. Each Phase 2 DAS went through a "burn-in" cycle for 30 days before being installed onto the test vehicles. A working fleet (Schrader Trucking of Jefferson City, Tennessee) was down-selected for partnership in the project, and six tractors and ten trailers (access provided gratis by Schrader Trucking) were instrumented in the fall of 2006 using the HTDC DASs. The first vehicle instrumented was closely monitored in the field for 30 days for issues with the equipment, installation, driver distraction, and software. A Memorandum of Understanding between DOE, Schrader Trucking, and ORNL was signed in late October 2006, and all test vehicles were deployed in the field operational test (FOT) by mid-November 2006.

Phase 3 of the HTDC project involved conducting an FOT, collecting and storing the data, developing the HTDC Duty Cycle Generation Tool (DCGenT), supporting the development of DOE's Powertrain Systems Analysis Toolkit (PSAT) module, and analyzing the collected data. The FOT was completed in November 2007. The six instrumented heavy trucks cumulatively hauled freight for more than 690,000 miles in an area approximately 1,000 miles in diameter, centered near Jefferson City, Tennessee. Ten trailers were also instrumented for this data collection effort. During the FOT, 60 channels of data were collected on each test truck for a 12-month period, resulting in the collection of 290 GB of raw data. The Phase 3 FOT is believed to be the most comprehensive real-world data for Class-8 long-haul performance known to exist. The data collected during the FOT included speed, fuel consumption, road grade, location, and weather conditions; and it is expected to be of value in truck fuel economy studies as called for in the Energy Independence and Security Act of 2007, and to provide a valuable resource to the EPA in its efforts to define a standardized duty cycle for Class-8 trucks.

The analysis of the FOT data permitted the computation of FEs for Class-8 trucks as a function of the types of tires mounted on the tractors and trailers and other measures such as weight. These calculations, made using fuel consumption information obtained from the vehicles' data buses, showed an overall FE above 6.0 mpg. This level of FE is on the upper limits of today's large-truck fleets and is mostly a result of the participating trucking company partner's being a technologically-minded organization, providing excellent programs in driver training, and having an extensive vehicle maintenance program (including, for example, maintaining constant tire pressures). The results of the data analysis showed that there was always a statistically significant improvement in FE with respect to the base case (i.e., dual tires on both the tractor and trailer, or duals-duals) when NGWBSTs are used on the tractor and/or trailer. Moreover, the FE improvement increases as the number of NGWBSTs on the truck increases, with observed improvements of around 6% when either the tractor or the trailer was equipped with NGWBSTs and more than 9% when both were mounted with NGWBSTs. When the data was parsed by tractor-trailer tire configuration and load level, the results of the analysis showed that there was again an improvement in FE with respect to the base case (i.e., duals-duals) when NGWBSTs were used. In fact, a closer look at the particular case in which all tires were NGWBSTs showed a considerable improvement in FE (above 10%) with respect to the base case, and those improvements were more pronounced as the load level increased. They were also statistically significant at the 99% level of confidence.

1.2 OVERALL PROJECT DESCRIPTION

The MTDC project involved efforts to collect, analyze, and archive data related to medium-truck operations in real-world driving environments. Such data and information will be useful to support technology evaluation efforts and to provide a means of accounting for real-world driving performance within medium-class truck analyses. The project was led by ORNL's CTA and involved private industry partners from various truck vocations.

The MTDC project is unique in that there currently does not exist a national database of characteristic duty cycles for medium trucks. Data was collected from four vocations (three vehicles within each one) while the vehicles conducted their normal business operations. The collection of this data did not perturb the vehicle's normal duty cycle. For the Part 1 FOT, three vehicles each from two vocations (urban transit and dry-box delivery) were instrumented for the collection of 1 year of operational data. Part 2 involved three vehicles each from the utility and towing and recovery vocations.

This FOT involved a number of tasks to collect and analyze real-world duty cycle data from medium trucks to accomplish the following objectives:

- Provide a source of real-world medium-truck performance data that can be utilized by DOE for making decisions related to future technology research investments.
- Provide a baseline of data that can be utilized to gauge 21CTP technology advancements.
- Provide a national source of real-world data for the medium-truck research community.
- Potentially provide data germane to EPA's goal of collecting emissions data from medium trucks in quantifiable driving environments.
- Potentially provide data germane to the Federal Motor Carrier Safety Administration's (FMCSA's) goal of collecting vehicle, driver, and carrier data in real time during normal vocational operation.

1.3 PARTNERSHIPS

The vehicles participating in the MTDC project are doing so through gratis partnerships in return for early access to the results of this study. Partnerships such as these are critical to FOTs in which real-world data is being collected. A partnership with FMCSA allowed the collection of additional safety-related signals beyond the normal set of duty cycle data collected in previous efforts.

1.3.1 H.T. Hackney

The H.T. Hackney Company[5] (HTH) is one of the largest wholesale distributors in the country, distributing products to 21 states. ORNL worked with personnel at the HTH Roane County, Tennessee, facility to collect data on three Class-7 units whose duty cycles involved delivery to local convenience stores. This fleet's safety consciousness and progressive attitude toward FE also made it an excellent venue for the installation of additional safety sensors to supplement the standard duty cycle data.

1.3.2 K-Trans Management

K-Trans Management operates the Knoxville Area Transit (KAT)[6], the Knoxville, Tennessee, transit system, providing services across Knoxville and other parts of Knox County. It partnered with ORNL to provide access to three of its Class-7 buses for data collection.

1.3.3 Fountain City Wrecker Service

Fountain City Wrecker Service (FCWS) is a towing and recovery company based in Fountain City, Tennessee, and operating primarily in the greater Knoxville area. In partnering with ORNL, it made three of its rollback Class-6 trucks available for data collection.

1.3.4 Knoxville Utilities Board

The Knoxville Utilities Board (KUB) provides utility services to the greater Knoxville, Tennessee, area. For this research, it made available three of its Class-8 vehicles equipped with PTO operation.

1.3.5 Federal Motor Carrier Safety Administration

Additionally, ORNL collaborated with FMCSA to determine if there were possible synergies between the MTDC data collection effort and FMCSA's need to learn more about the operation and duty cycles of medium trucks. FMCSA's primary interest was in collecting safety data relative to the driver, carrier, and vehicle. Further, FMCSA is in the process of developing functional requirements for wireless transfer of data from a commercial vehicle to the roadside.

Beyond the standard duty cycle data collection system used in previous DOE duty cycle research, additional sensors were installed on three Part 1 test vehicles (Class-7 single-axle tractor-trailers) to collect several safety-related signals of interest to FMCSA. These additional sensors were provided through a partnership with FMCSA, which provided for the additional cost of incorporating these sensors into the DAS. The real-time brake stroke, tire pressure, and weight information obtained from these sensors makes possible a number of safety-related analyses such as determining the frequency and severity of braking events and tracking tire pressure changes over time.

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[5] http://www.hthackney.com/.

[6] http://www.katbus.com/.

2. FIELD OPERATIONAL TEST

For the MTDC Part 1 FOT, three vehicles each from two vocations (urban transit and dry-box delivery) were instrumented for 1 year of data collection (2009–2010). The Part 2 MTDC FOT involved the towing and recovery and utility vocations, and data was collected for 1 year in the 2010–2011 timeframe.

2.1 VOCATIONAL ASSESSMENT

Within the medium weight category of trucks, there is such a variety of applications that it is virtually impossible to identify a single typical duty cycle for the weight class. Therefore, the decision was made to select a few major medium-truck vocations for the MTDC FOT. A vocational assessment[7] was conducted to identify several recommended vocations for participation in the FOT.

2.1.1 Initial Down-Selection

The following vocations were originally under consideration for participation in the FOT based on available 2002 VIUS data:

- Dry-box delivery
- Beverage delivery
- Refrigerated/frozen delivery
- Package delivery
- Utility (where PTO is used)
- Public transit
- School bus
- Towing and recovery
- Farming

Because of the limited number of DASs available and the desire to collect seasonal data, not all of these vocations could participate in the FOT within a reasonable timeframe. The list of vocations was down-selected to six to give a typical representation of medium trucks based on vehicle miles traveled, hours of operation per day, typical payload, area of operation, PTO operation, auxiliary cargo heating and cooling, and daily idle time.

Farming vehicles were removed from the list because most medium trucks used in farming operations are not over-the-road vehicles in regular use. The package delivery vocation was also eliminated because although it may be distinct from other vocations, the data collected would be applicable to only the few companies in this industry; few other vocations would find this duty cycle characteristic of their operations.

The rental truck vocation was also considered for inclusion because it represents a significant number of medium trucks—particularly Class-6 trucks. However, in addition to its being a niche market (similar to package delivery), equipment security was a significant risk area. Unlike other vocations, the drivers of these vehicles would not typically be employed by the company and therefore presented a data and equipment security risk.

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[7] Internal ORNL report

Another vocation under consideration was beverage delivery. However, when the potential partner proved unable to participate, it was decided that the duty cycle of this vocation may be similar to that of refrigerated/frozen delivery and dry-box delivery vehicles. Thus a replacement for this fleet was not pursued.

2.1.2 Recommended Vocations

Following the formal down-selection, the following vocations were recommended for the FOT.

2.1.2.1 Dry-Box Delivery

Dry box delivery trucks typically operate during normal business hours and travel routes within a certain distance from their distribution centers. Their payloads range from near-capacity to empty throughout the day as deliveries are made.

2.1.2.2 Refrigerated/Frozen Delivery

This vocation was expected to have a lower FE than dry-box delivery trucks because of the energy requirements of the refrigeration system. Trucks involved in this type of delivery were expected to go out fully loaded on a daily basis. Of particular interest is the seasonal variation in the energy demands of the refrigeration system.

2.1.2.3 Utility

The duty cycles of utility trucks are unique in that the typical utility truck spends relatively little time traveling (and thus has a much lower annual mileage than other medium trucks). It was expected that these trucks would typically spend most of their operating time in PTO operation, up to 8 h in a 10 h operational day. It was expected that the utility trucks would experience negligible change in weight and travel in both rural and urban areas.

2.1.2.4 Urban Transit

Urban transit buses experience stop-and-go operation throughout the day, often driving in congested areas. Although these vehicles typically drive predictable routes, the collection of data for an entire 12 month period would reveal seasonal variations.

2.1.2.5 Rural Pupil Transportation

The inclusion of a rural school bus would permit the collection of an exclusively rural duty cycle. Unlike other vocations selected, there would be times during the year when these vehicles were not in operation. This duty cycle is unique because although it is based on a regular schedule, it does not typically include hours of operation during the entire business day.

2.1.2.6 Towing and Recovery

Unlike the other vocations selected, vehicles employed in towing and recovery do not have regular, predictable duty cycles. Furthermore, the payload will likely be either fully loaded or unloaded. Like the utility trucks, these vehicles are expected to travel in both urban and rural areas and make regular use of their PTOs.

2.1.3 Selected Vocations

Based on further correspondence with the project sponsor, the list of vocations to be included in the FOT was reduced to the following four vocations.

- Local delivery
- Urban transit
- Utility
- Towing and recovery

The test methodology used in the FOT allowed for a full year of duty cycle data to be collected from three vehicles from each vocation. The first two vocations from the bulleted list above were involved in the Part 1 FOT; the Part 2 FOT involved the final two vocations with an emphasis on PTO operation.

2.2 DATA ACQUISITION SYSTEM AND SENSORS

A DAS was placed on each test vehicle to collect relevant duty cycle data for wireless upload and subsequent analysis. Native signals were obtained directly from the vehicle's J1939 and J1708 data buses. The DAS enclosure is shown in Figure 1.

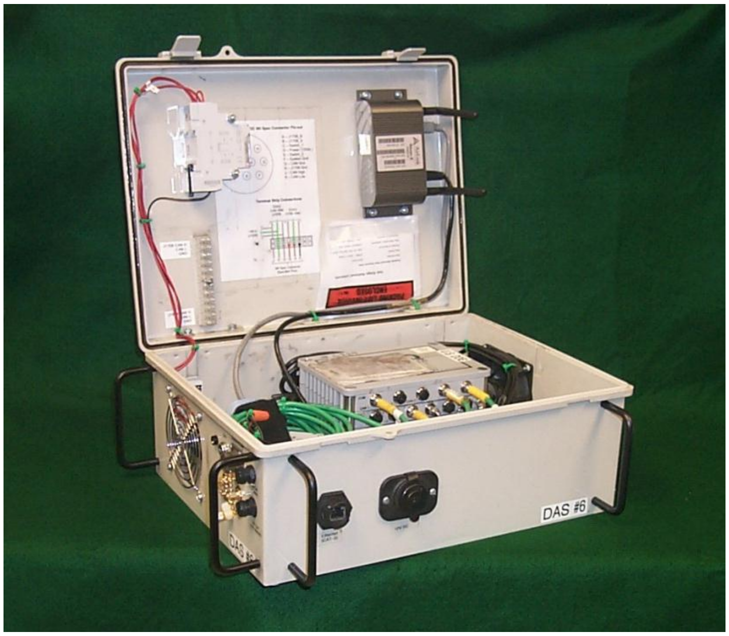

Figure 1. MTDC DAS.

To simplify wiring, all vehicle connections were made to a smaller DAS interface box (DASIB), and a single long cable connected the DASIB to the DAS. The internal wiring of the DASIB was customized for each vehicle to allow the DASIB ports to be used for a separate wiper switch, data bus, and sensors to be connected while providing a standardized interface with the DAS across all vehicles. The DASIB and associated wiring are shown in Figure 2.

Figure 2. DASIB and associated cables.

The VBOX II Lite (Figure 3) collected global positioning system (GPS) -related information—including speed, acceleration, and location—at a rate of 5 Hz for the Part 1 FOT. This data was communicated via the controller area network (CAN, J1939) protocol. For the Part 2 FOT, an eDAQ-based GPS unit was used, providing similar information at 5 Hz.

Figure 3. VBOX II Lite GPS unit.

The Air-Weigh LoadMaxx (Figure 4) is a self-weighing system that determines the GVW by means of pressure transducers and/or strain gauges and posts the weight to the vehicle’s J1939 data bus. The delivery vehicles, transit vehicles, and towing and recovery vehicles were instrumented with this system. Because the test vehicles from the utility vocation did not typically experience a variable load, they were not instrumented; instead, a single set of weight readings were obtained for these vehicles during the Part 2 FOT.

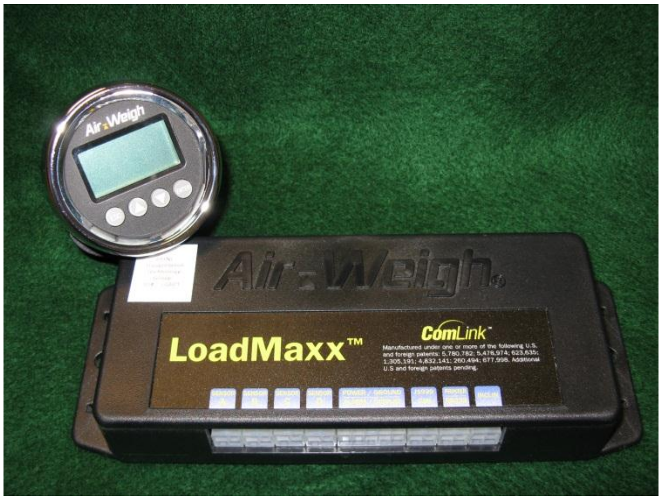

Figure 4. Air-Weigh LoadMaxx kit.

The eDAQ-lite data acquisition unit (Figure 5) collected and stored data from the vehicle's J1939 and J1708 data buses and connected J1939 sensors (i.e., the VBOX and Air-Weigh units). For the purposes of the FOT, it was configured to record all data at a rate of 5 Hz. The eDAQ-lite's internal data storage allowed for periodic uploads.

Figure 5. EDAQ-lite data acquisition unit.

The Raven X EVDO V4221 (Figure 6) is the cellular modem that facilitated the communication between the eDAQ-lite and the user via the internet. The modem functioned as a wireless gateway, allowing data retrievals and system checks to be performed remotely.

In partnership with FMCSA, two additional safety sensors were installed on the combination vehicles (Part 1 FOT): the MGM e-Stroke brake monitoring system (Figure 7) and the Tire SafeGuard tire pressure monitoring system (TPMS) (Figure 8). Both of these systems posted data to the J1939 data bus, enabling these signals to be read without any additional DAS interface hardware.

Figure 6. Raven X EVDO cellular modem.

Figure 7. MGM e-Stroke control unit.

Figure 8. Tire SafeGuard display and transducers.

2.3 TEST VEHICLES

For Part 1 of the MTDC FOT, three vehicles each from two vocations, Class-7 combination truck (tractor-trailer) and urban transit bus, were instrumented with the previously-constructed HTDC DASs to collect 12 months of real-world operational data. Vehicles from the remaining vocations (utility and towing and recovery) were instrumented with the DASs in Part 2 of the MTDC FOT. Because the vocation and body type of the test vehicle were more important to the project than the vehicle class, heavy truck data was collected for the utility vocation.

Medium tractor-trailers were represented by the local delivery vocation. HTH made available three 2005/2007 International day-cab tractors, model 8600, which regularly haul 28 ft pup trailers. These vehicles have routes within a 60 to 80 mile radius of HTH's Roane County facility. The trailers have three compartments: insulated, refrigerated, and frozen. Because the cooling for the trailer is powered separately (i.e., a separate diesel engine run from a separate fuel tank located on the trailer), there are no additional parasitic fuel losses (which would influence FE) due to the refrigerated units. These vehicles' regular daily operation involves delivery of 3,000 to 10,000 lb of cargo while generally covering 125 miles on a given day. A typical HTH vehicle is pictured in Figure 9.

Figure 9. H.T. Hackney 2007 International 8600.

The transit buses were made available for the Part 1 MTDC FOT by K-Trans Management, which operates KAT. These vehicles are 2005 Optima LF-34 buses. Although additional safety technologies were not installed on these vehicles, the standard DAS and Air-Weigh self-weighing units were used. These vehicles' regular operation involves short trips throughout the Knoxville area; although most of the routes traveled by these buses consist of surface streets, highway data was also collected. A typical test vehicle is shown in Figure 10.

The utility vehicles were made available by KUB. These consist of a Class-8 1998 Paystar 500 6×6, a Class-8 2010 International DuraStar, and a Class-8 2004 International 7300. These vehicles were recommended by personnel at KUB because of the variety of routes they represent and PTO operation. Although a smaller vehicle was initially investigated as the possible third test vehicle, it could not be used because of the absence of key signals on the data bus such as torque, revolutions per minute, and PTO operation. One of the test vehicles used in the FOT is shown in Figure 11.

Figure 10. KAT transit bus.

Figure 11. Test vehicle from the utility vocation.

Wreckers were represented by rollback type towing and recovery vehicles. FCWS made available one International 4300 and two Ford F650s. These vehicles were selected because they are used more frequently than many of the other medium trucks owned by the company. They operate in the greater Knoxville, Tennessee, area hauling a variety of vehicles from passenger cars to other medium trucks. One of these test vehicles is shown below in Figure 12.

Figure 12. Test vehicle from the towing and recovery vocation.

Key features of each test vehicle are summarized in Table 1. The vehicle number shown in the first column is used throughout this document to specify individual test vehicles.

Table 1. Summary of MTDC Test Vehicles

Vehicle no.	Vocation	Body type	Class	Make and model	Trans-mission	Engine	GVWR (lb)	Empty weight (lb)
1	Local delivery	Tractor-trailer	7	International 8600	Manual	CAT C11 Acert 11.1 L	32,000	28,640
2	Local delivery	Tractor-trailer	7	International 8600	Automatic	Cummins ISM-370 10.8 L	32,000	26,976
3	Local delivery	Tractor-trailer	7	International 8600	Automatic	Cummins ISM-370 10.8 L	32,000	26,920
4	Urban transit	Bus	7	Optima LF34	Automatic	Cummins ISB-02	30,000	22,198
5	Urban transit	Bus	7	Optima LF34	Automatic	Cummins ISB-02	30,000	22,257
6	Urban transit	Bus	7	Optima LF34	Automatic	Cummins ISB-02	30,000	22,274

Table 1. Summary of MTDC Test Vehicles (Continued)

Vehicle no.	Vocation	Body type	Class	Make and model	Trans-mission	Engine	GVWR (lb)	Empty weight (lb)
7	Utility	Bucket truck	8	Paystar 5000	Manual	International DT530 8.7 L	Unknown	43,780
8	Utility	Bucket truck	8	Durastar 4400	Automatic	MaxxForce DT466 7.6 L	37,000	28,940
9	Utility	Bucket truck	8	International 7300	Automatic	International DT466 7.6 L	37,000	32,600
10	Towing/ recovery	Rollback	6	International 4300	Manual	International DT466 7.6 L	26,000	15,700
11	Towing/ recovery	Rollback	6	Ford F650	Automatic	Cummins IBS 5.9 L	26,000	15,600
12	Towing/ recovery	Rollback	6	Ford F650	Automatic	Cummins IBS5.9 L	26,000	16,750

2.4 COLLECTED SIGNALS

Because of the differences in vehicle data buses, not all desired signals were available for all vehicles. Table 2 shows the list of signals and their availability on the vehicles' J1939 and J1708 data buses. The signals available for each vocation are similar but may not be identical where different data buses are used. For example, the J1939 data bus signals are often updated more frequently than their J1708 counterparts. Typically, SI units are used for J1939 data, whereas the J1708 signals are occasionally reported in US customary units.

For a vehicle with a J1939 data bus, the torque values reported by the data bus are in terms of percentage of a reference value. This "engine reference torque" is a static value that is valid as long as the engine is not reprogrammed with a different engine map (which is rarely done). This value can therefore be read from the data bus once for use in interpreting duty cycle data. During the test vehicle assessment, this value was found to be 2,118 Nm for the delivery vehicle tested and 1,024 Nm for the transit bus.

For the actual data collection, certain on/off status flags were incorporated into a single channel for more efficient use of data acquisition resources. For example, signals 23–24 were combined into a brake/clutch switch channel, and signals 25–30 were combined into a cruise control status channel. The individual indicators may be easily recovered via post-processing of the data.

Table 3 lists additional signals available from sensors incorporated into the DAS. These additional sensors include the GPS-based VBOX II Lite (Part 1) and the self-weighing Air-Weigh unit. In order to collect basic precipitation indication data, a channel was used to monitor the wiper switch as well.

Table 2. Signals native to the vehicle

No.	Description of signal	FOT Part 1 vehicles						FOT Part 2 vehicles					
		1	2	3	4	5	6	7	8	9	10	11	12
1	High resolution total vehicle distance	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
2	Road speed limit status	Y	Y	Y	Y	Y	Y	Y*	Y	Y*	Y*	Y	Y
3	Wheel-based vehicle speed	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
4	Front axle speed	N	Y	Y	Y	Y	Y	N	Y	N	N	Y	Y
5	Engine speed	N	Y	Y	N	N	N	Y*	Y	Y	Y	Y	Y
6	Current gear	N	Y	Y	N	N	N	N	Y	Y	N	Y	Y
7	Selected gear	N	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y
8	Actual gear ratio	N	Y	Y	N	N	N	N	Y	Y	N	Y	Y
9	Output shaft speed	N	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y
10	Transmission current range	N	Y	Y	Y*	Y*	Y*	N	Y	Y	N	Y	Y
11	Transmission requested range	Y	Y	Y	Y*	Y*	Y*	N	Y	Y	N	Y	Y
12	Engine oil temperature	Y	Y	Y	N	N	N	Y*	Y	Y	Y	N	N
13	Intake manifold temperature	Y	Y	Y	Y	Y	Y	N	Y	Y*	N	Y	Y
14	Engine coolant temperature	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
15	Fuel rate	Y	Y	Y	Y	Y	Y	Y*	Y	Y*	Y*	Y	Y
16	Instantaneous fuel economy	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
17	Actual engine—percent torque	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
18	Accelerator pedal position	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
19	Percent load at current speed	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
20	Driver's demand engine—percent torque	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y

Table 2. Signals native to the vehicle (Continued)

No.	Description of signal	FOT Part 1 vehicles						FOT Part 2 vehicles					
		1	2	3	4	5	6	7	8	9	10	11	12
21	Nominal friction percent torque	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
22	Clutch and brake switches	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
23	Cruise control switches	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
24	Cruise control set speed	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
25	Power takeoff governor state	N	Y	N	Y	Y	Y	N	Y	Y	N	Y	Y
26	Power takeoff set speed	N	Y	N	Y	Y	Y	Y*	Y	Y*	Y*	Y	Y
27	Total power takeoff hours	Y	Y	N	Y	Y	Y	N	Y	N	Y*	Y	Y
28	Power takeoff status flags	–	–	–	–	–	–	Y	N	N	Y	N	N
29	Actual retarder—percent torque	Y	Y	Y	N	N	N	N	N	N	N	Y	Y
30	Retarder torque mode	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y
31	Engine retarder selection	Y	Y	Y	N	N	N	N	N	N	N	Y	Y
32	Intended retarder percent torque	N	Y	Y	N	N	N	N	N	N	N	Y	Y
33	Electrical voltage	Y	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
34	Fan drive state	Y	Y	Y	Y	Y	Y	N	Y	N	N	Y	Y
35	AC high pressure fan switch	N	Y	Y	Y	Y	Y	N	N	N	N	Y	Y
36	Barometric pressure	N	Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
37	Boost pressure	Y*	Y*	Y*	Y*	Y*	Y*	Y*	Y*	Y*	Y*	Y*	Y*
38	Ambient air temperature	N	N	N	N	N	N	Y	Y	N	N	N	N
39	Wiper switch status	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

*Indicates information available from J1708 data bus rather than J1939

Table 3. Availability of signals from other sensors

No.	Description of signal	FOT Part 1 vehicles (VBOX)						FOT Part 2 vehicles (eDAQ)					
		1	2	3	4	5	6	7	8	9	10	11	12
40	Satellite count	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
41	Time in s since midnight UTC	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
42	Longitude	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
43	Latitude	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
44	Altitude	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
45	Heading	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
46	Velocity	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
47	Vertical velocity	Y	Y	Y	Y	Y	Y	–	–	–	–	–	–
48	Longitudinal acceleration	Y	Y	Y	Y	Y	Y	–	–	–	–	–	–
49	Lateral acceleration	Y	Y	Y	Y	Y	Y	–	–	–	–	–	–
50	Trip distance	Y	Y	Y	Y	Y	Y	–	–	–	–	–	–
51	Steer axle weight	Y	Y	Y	Y	Y	Y	–	–	–	Y	Y	Y
52	Drive axle weight	Y	Y	Y	Y	Y	Y	–	–	–	Y	Y	Y

In addition to the signals already listed, safety-related sensors were provided via a partnership with FMCSA. Two areas of interest to FMCSA are brake system operation and dynamic weight changes to vehicle components and tires during operation. The e-Stroke device by MGM Brake and the Tire SafeGuard TPMS post the signals described in Table 4 to the J1939 data bus; these signals provided some of the data of interest to FMCSA related to brake operation and tire pressure.

2.5 PART 1 FOT

2.5.1 Installation and Shakedown Testing

Instrumentation of the test vehicles involved making connections to the vehicles' internal wiring to tap into the data bus, obtain power for the DAS, and monitor the ignition switch and windshield wipers. Cable runs to and from sensors were routed so as to allow for sustained testing and occupant safety. Consideration was also given to shielding these cables from engine/exhaust heat and damage from objects thrown from the roadway.

Table 4. Additional safety signals (tractors of delivery vehicles only)

No.	Description	Sensor
53	Brake actuator status–left front	E-Stroke
54	Brake actuator status–right front	E-Stroke
55	Brake actuator status–left rear	E-Stroke
56	Brake actuator status–right rear	E-Stroke
57	Brake application pressure	E-Stroke
58	Tire pressure–left front	Tire SafeGuard
59	Tire pressure–right front	Tire SafeGuard
60	Tire pressure–left rear outside	Tire SafeGuard
61	Tire pressure–left rear inside	Tire SafeGuard
62	Tire pressure–right rear inside	Tire SafeGuard
63	Tire pressure–right rear outside	Tire SafeGuard
64	Tire temperature–left front	Tire SafeGuard
65	Tire temperature–right front	Tire SafeGuard
66	Tire temperature–left rear outside	Tire SafeGuard
67	Tire temperature–left rear inside	Tire SafeGuard
68	Tire temperature–right rear inside	Tire SafeGuard
69	Tire temperature–right rear outside	Tire SafeGuard
70	Tire pressure threshold detection–left front	Tire SafeGuard
71	Tire pressure threshold detection–right front	Tire SafeGuard
72	Tire pressure threshold detection–left rear outside	Tire SafeGuard
73	Tire pressure threshold detection–left rear inside	Tire SafeGuard
74	Tire pressure threshold detection–right rear inside	Tire SafeGuard
75	Tire pressure threshold detection– right rear outside	Tire SafeGuard

Prior to installation, ORNL staff discussed the location, orientation, and connections for the DAS with managers and technicians at the partner facilities to ensure that the equipment would be installed so as to be “transparent” to the vehicle operator and not require driver interaction, while still permitting safe access by test engineers when necessary. This partner input also ensured that the installation would not damage the structure of the test vehicles, affect their appearance once the equipment was removed, or decrease the value of the vehicle beyond normal depreciation. ORNL provided the materials and accompanying instructions for installation of cabling and GPS antennas and installed the actual DASs on the partners’ prepared vehicles. All equipment was securely fastened in place to prevent driver distraction and to avoid damage to the test equipment.

Installation and calibration of the self-weighing system was performed by Air-Weigh personnel. The calibrations of the Air-Weigh units were performed at the partners’ respective bases of operations. Portable scales for the calibration were provided by the Tennessee Department of Safety and Homeland Security via a partnership with FMCSA.

Upon installation of the DAS, the sensors were individually monitored through a computer with a wired connection to the eDAQ-lite. When the proper operation of the installed sensors was confirmed, the cellular modem was connected and the ability to communicate with the system remotely via the internet was checked. When all systems appeared to be functioning as intended, the vehicle was released to resume normal operations.

Prior to the start of the FOT, in order to diagnose any sensor and data problems that were not recognized during the equipment configuration stage, one test vehicle was instrumented for approximately 1 month of shakedown testing. During this time, minor adjustments and corrections were made to equipment settings, and frequent data uploads were performed. Procedures to be used throughout the FOT were finalized, and data analysis was performed on a small scale in order to identify problems in the analysis software so that they could be corrected before the full FOT. One goal of this preliminary testing was to verify that the use of a cellular modem to interface with the eDAQ-lite through the internet provided an efficient and robust data collection solution. At the successful conclusion of the shakedown testing, the remaining test vehicles were instrumented and deployed.

2.5.2 Launch of the FOT and MOA Signing

Data collection began in May 2009 with the official signing of the Memoranda of Agreement (MOA) at a ceremony on July 7, 2009, at the NTRC[8] located in Knoxville, Tennessee (Figure 13). Representatives from DOE, DOT, HTH, K-Trans Management, and ORNL participated in this event, which was well attended by the media.

Figure 13. MOA signing ceremony (July 7, 2009).

2.5.3 De-Instrumentation

The DAS and sensor suites were removed from each of the test vehicles at the conclusion of the FOT. Most of the de-instrumentation was performed by technicians at the partners' facilities. Because it was not cost-effective to remove the safety sensors (provided by FMCSA) from the combination test vehicles and re-install them for future projects, these sensors remained installed on those test vehicles for potential future research and use by HTH in its normal operations. Additional cables associated with discrete sensors or systems were left in place at the partners' discretion. This decision saved DOE and ORNL the cost of removing the cabling from the test vehicle (as this type of cabling had no remaining value to DOE or ORNL once removed). The DAS and sensors were returned to ORNL for use in the Part 2 MTDC

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[8] http://www.ntrc.gov/ .

effort. The fleet vehicle was “restored” as needed after the equipment was removed; for example, cable feedthrough holes were plugged, dash cutouts were covered, and electrical connections were terminated.

2.6 PART 2 FOT

2.6.1 Installation and Calibration

An assessment of the test vehicles was performed from May to October 2010 to determine the suitability of each suggested vehicle for inclusion in the data collection effort. For the Part 2 effort, the fleets selected three towing and recovery vehicles of two makes/models and three different utility vehicles for participation in the FOT. Staff at each partner’s shop facilitated the integration of the DASs and associated wiring and equipment; the Air-Weigh installations in the towing and recovery vehicles were performed by technicians from that company. Following installation of the DASs, Air-Weigh units were calibrated with the support of the Tennessee Highway Patrol (THP).

2.6.2 Launch of the Part 2 FOT

The Part 2 data collection was launched with the first vehicle entering the Part 2 FOT in September 2010. The FOT initially involved three towing and recovery vehicles and only two utility vehicles. Because of problems identifying a third test vehicle with a data bus meeting the project requirements, the final utility test vehicle entered the test late, in December 2010.

2.6.3 De-Instrumentation

All six test vehicles were de-instrumented in December 2011. The DASs and all associated instrumentation and wiring installed for the FOT were removed and the vehicles were returned to their original condition.

3. SOFTWARE TOOLS DEVELOPED

3.1 DATA BUS ANALYSIS UTILITY

Prior to any data collection effort, a determination must be made as to what signals are available on each test vehicle's data bus. Although the J1939 and J1587 (data layer for J1708) Society of Automotive Engineers standards provide information on where signals might be on those respective data buses (the two databases used by heavy trucks and some medium trucks), the actual signals available and the specific parameters vary from vehicle to vehicle. ORNL developed the data bus analysis utility (DBAU) to efficiently identify the specific signals and locations, making it possible to tailor the signal database for each test vehicle with a short segment of data from the vehicle data bus (about 10 min worth of data).

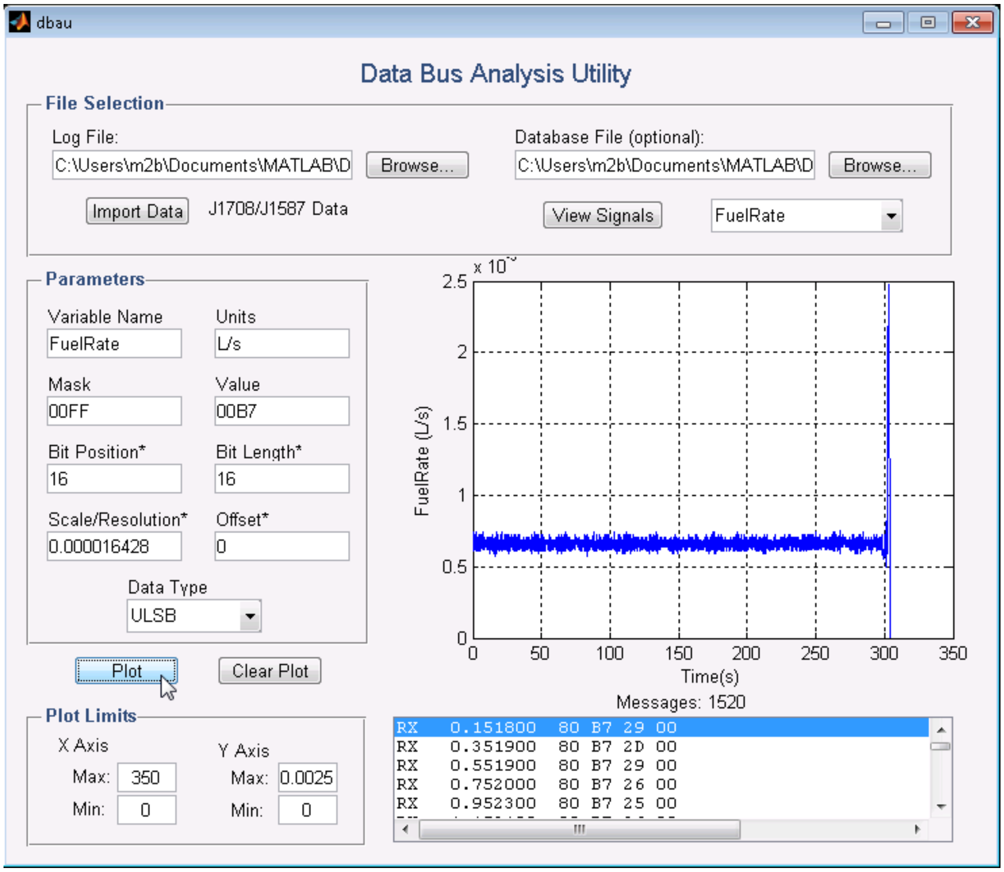
To use this Matlab-based software, the eDAQ is set up to log several minutes of vehicle data bus activity including driving time, idling time, PTO operation, and similar activities. The DBAU is launched and the data bus log is loaded into the software, where the type of data bus (CAN/J1939 or J1708) is automatically identified. The database file used to interpret the data will, by default, be a generic file; however, a custom file may be used instead. Once the parameters from the database file have been loaded in the graphical user interface (GUI), a drop-down list will be populated with all of the channels specified in the database file. Selecting a signal from this list auto-populates the parameters used to identify and interpret that signal. These parameters may be modified as needed before plotting. Once the data is plotted, the messages shown below the plotting area are limited to those meeting the criteria specified by the parameters. This allows the user to immediately identify which signals are available, which may need to be requested specifically by the DAS, and which need to have tailored screening parameters. Any modifications to the screening parameters can be made on the spot to fine-tune the database for that particular test vehicle. The GUI is shown in Figure 14.

Prior to the development of the DBAU, data bus assessments typically required two site visits and approximately 2 days of analysis for each vehicle type. With this tool, data bus assessments can be performed in a single site visit.

3.2 WIRELESS DATA DOWNLOAD TOOL

To efficiently collect data from test vehicles based in two different locations, cellular modems were integrated into each DAS. This approach permitted test data to be uploaded via the internet, making regular site visits unnecessary for properly functioning systems.

The Visual-Basic–based Wireless Data Download Tool developed by ORNL simplified the data retrieval task and increased data security and integrity, allowing researchers to quickly react when any onboard sensor developed problems. This software accessed each DAS via its cellular modem, retrieving data at scheduled times (see Figure 15). Upon receipt, this information was converted from the binary format used by the DAS to a more software-usable ASCII format. Copies of the data were stored on both remote and local drives, and an email summary of the files that were downloaded each evening was sent to ORNL research staff supervising the data retrieval.



Log File: C:\Users\m2b\Documents\MATLAB\D

J1708/J1587 Data

Database File (optional): C:\Users\m2b\Documents\MATLAB\D

FuelRate

Variable Name: FuelRate

Units: L/s

Mask: 00FF

Value: 00B7

Bit Position*: 16

Bit Length*: 16

Scale/Resolution*: 0.000016428

Offset*: 0

Data Type: ULSB

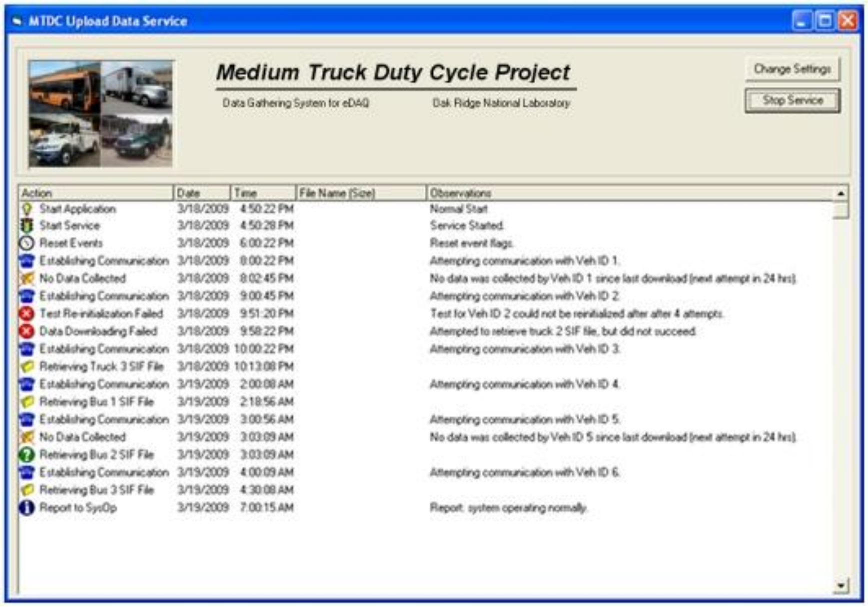
X Axis Max: 350 Min: 0

Y Axis Max: 0.0025 Min: 0

Messages: 1520

```
RX    0.151800   80 B7 29 00
RX    0.351900   80 B7 2D 00
RX    0.551900   80 B7 29 00
RX    0.752000   80 B7 26 00
RX    0.952300   80 B7 25 00
```

Figure 14. User interface for the DBAU.



Action	Date	Time	File Name (Size)	Observations
Start Application	3/18/2009	4:50:22 PM		Normal Start
Start Service	3/18/2009	4:50:28 PM		Service Started.
Reset Events	3/18/2009	6:00:22 PM		Reset event flags.
Establishing Communication	3/18/2009	8:00:22 PM		Attempting communication with Veh ID 1.
No Data Collected	3/18/2009	8:02:45 PM		No data was collected by Veh ID 1 since last download (next attempt in 24 hrs).
Establishing Communication	3/18/2009	9:00:45 PM		Attempting communication with Veh ID 2.
Test Re-initialization Failed	3/18/2009	9:51:20 PM		Test for Veh ID 2 could not be reinitialized after after 4 attempts.
Data Downloading Failed	3/18/2009	9:58:22 PM		Attempted to retrieve truck 2 SIF file, but did not succeed.
Establishing Communication	3/18/2009	10:00:22 PM		Attempting communication with Veh ID 3.
Retrieving Truck 3 SIF File	3/18/2009	10:13:08 PM		
Establishing Communication	3/19/2009	2:00:08 AM		Attempting communication with Veh ID 4.
Retrieving Bus 1 SIF File	3/19/2009	2:18:56 AM		
Establishing Communication	3/19/2009	3:00:56 AM		Attempting communication with Veh ID 5.
No Data Collected	3/19/2009	3:03:09 AM		No data was collected by Veh ID 5 since last download (next attempt in 24 hrs).
Retrieving Bus 2 SIF File	3/19/2009	3:03:09 AM		
Establishing Communication	3/19/2009	4:00:09 AM		Attempting communication with Veh ID 6.
Retrieving Bus 3 SIF File	3/19/2009	4:30:08 AM		
Report to SysOp	3/19/2009	7:00:15 AM		Report: system operating normally.

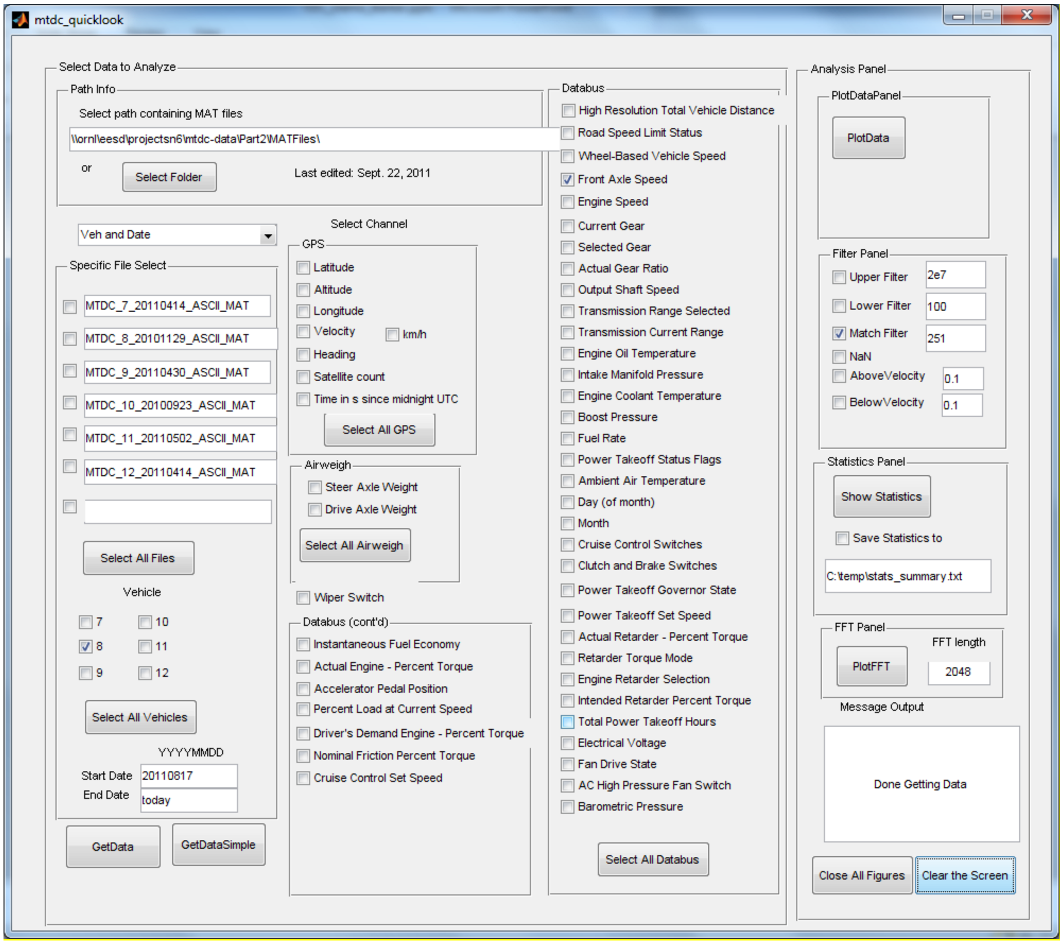
Figure 15. User interface for Wireless Data Download Tool.

For the 12 FOT vehicles, the uncompressed (ASCII) data files reached a size of approximately 310 GB of raw data. Because of the large volume of data to be collected, regular data uploading, preliminary checking, and data archiving were performed throughout the FOTs. This also permitted the recognition of sensor problems soon after they developed, minimizing data loss due to equipment malfunctions.

The data retrieval process generated several copies of the data; two of these copies were stored on separate external hard drives on the project computer running the wireless data retrieval tool. An additional copy of the downloaded data was kept on an ORNL server maintained for this purpose at the ORNL campus (located approximately 12 miles from the NTRC), backed up on a daily basis to protect against data loss. The retrieval and archiving process was fully automated and did not require human intervention. Each day, the system emailed to the ORNL researchers a summary of the data downloaded from each vehicle, highlighting any sensors that showed a percentage of errors above a predefined threshold. This allowed problems to be quickly identified and corrected either by accessing the DAS over the air or by physically accessing the system and making the necessary adjustments or replacements.

3.3 DATA QUICKLOOK TOOL

Following data retrieval, spot checks of channels were performed from time to time to confirm that data collection was proceeding as planned. This Matlab-based software was designed to enable the user to easily plot and examine channels from each data source (data buses, specific research instrumentation, and GPS) and to facilitate followup on any data flagged in the automated data retrieval notification. The Data QuickLook Tool interface (Figure 16) allows the user to select the files and channels desired for graphing (Figure 17). A review plot from each data source confirms the proper functioning of the DAS or reveals issues with the data (for example, identifying discrepancies between data-bus– and GPS-based speed signals).



Select path containing MAT files: \\ornl\eesd\projectsn6\mtdc-data\Part2\MATFiles\

Last edited: Sept. 22, 2011

Veh and Date

☐ MTDC_7_20110414_ASCII_MAT
☐ MTDC_8_20101129_ASCII_MAT
☐ MTDC_9_20110430_ASCII_MAT
☐ MTDC_10_20100923_ASCII_MAT
☐ MTDC_11_20110502_ASCII_MAT
☐ MTDC_12_20110414_ASCII_MAT

Vehicle: ☐ 7 ☑ 8 ☐ 9 ☐ 10 ☐ 11 ☐ 12

Start Date 20110817
End Date today

☑ Front Axle Speed

☐ Upper Filter 2e7
☐ Lower Filter 100
☑ Match Filter 251
☐ NaN
☐ AboveVelocity 0.1
☐ BelowVelocity 0.1

☐ Save Statistics to C:\temp\stats_summary.txt

FFT length 2048

Message Output: Done Getting Data

Figure 16. User interface for the Data QuickLook Tool.

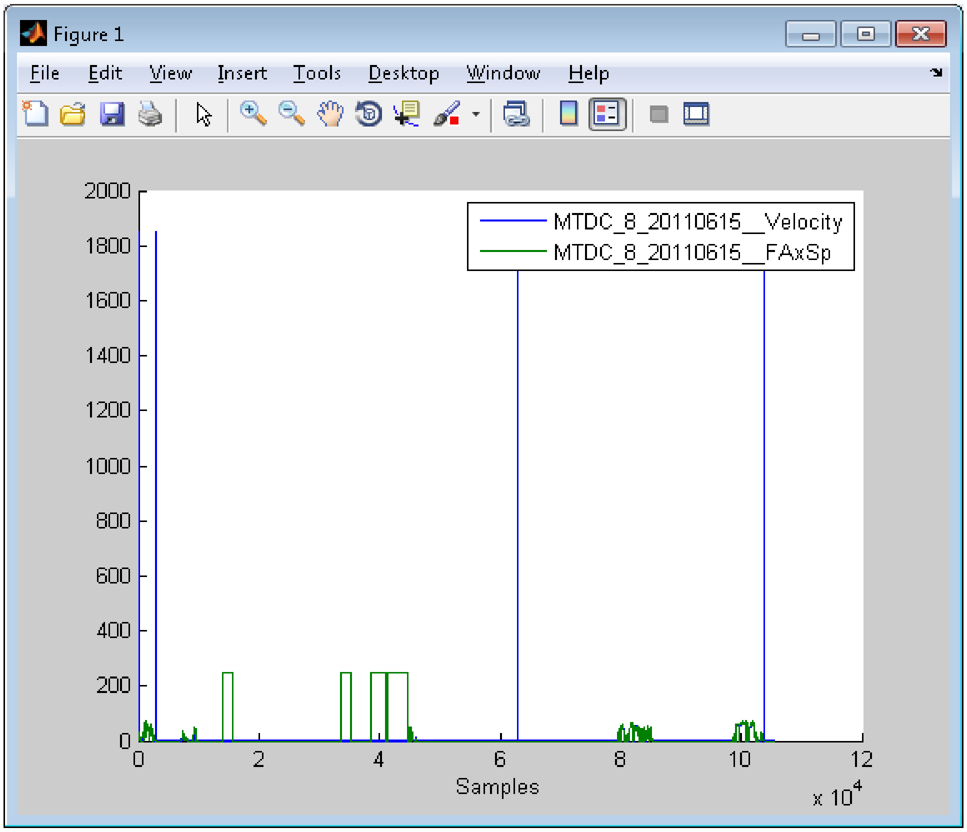


Figure 17. Sample plot from Data QuickLook Tool.

3.4 DATA EXTRACTOR AND ANALYSIS TOOL

The data collected in the HTDC and in both MTDC FOTs has a very strong spatial component, since it is data collected on moving vehicles. Some of the information collected could be retrieved and analyzed disregarding that spatial component; however, any analysis or any modeling involving FEs requires taking into consideration the location of the vehicles to account for variables such as roadway grade, vehicle traveling in urban vs. rural areas (more traffic congestion is expected in the former), vehicle traveling on freeways vs. surface streets, and other conditions that are related to location.

To efficiently find and retrieve specific information from the large database of information collected in this project (i.e., a total of more than 600 GB for the HTDC and MTDC projects), it was necessary to index the information and to create a database of pointers that would allow for the quick retrieval of data records that comply with possibly multiple search criteria specified by the analyst. Several aspects of the collected information that were expected to play a relevant role in the data analysis were taken into account in the development of this tool. For example, the following situations were explored:

- a vehicle moving on a freeway vs. a vehicle moving on a surface street,
- a vehicle moving in an urban area vs. a vehicle moving in a rural area,
- a vehicle moving under rainy conditions vs. a vehicle moving under clear weather,
- a vehicle moving during the morning peak hour vs. a vehicle moving during mid-morning off-peak hours,
- a vehicle moving vs. a vehicle in a stationary position, and
- many others.

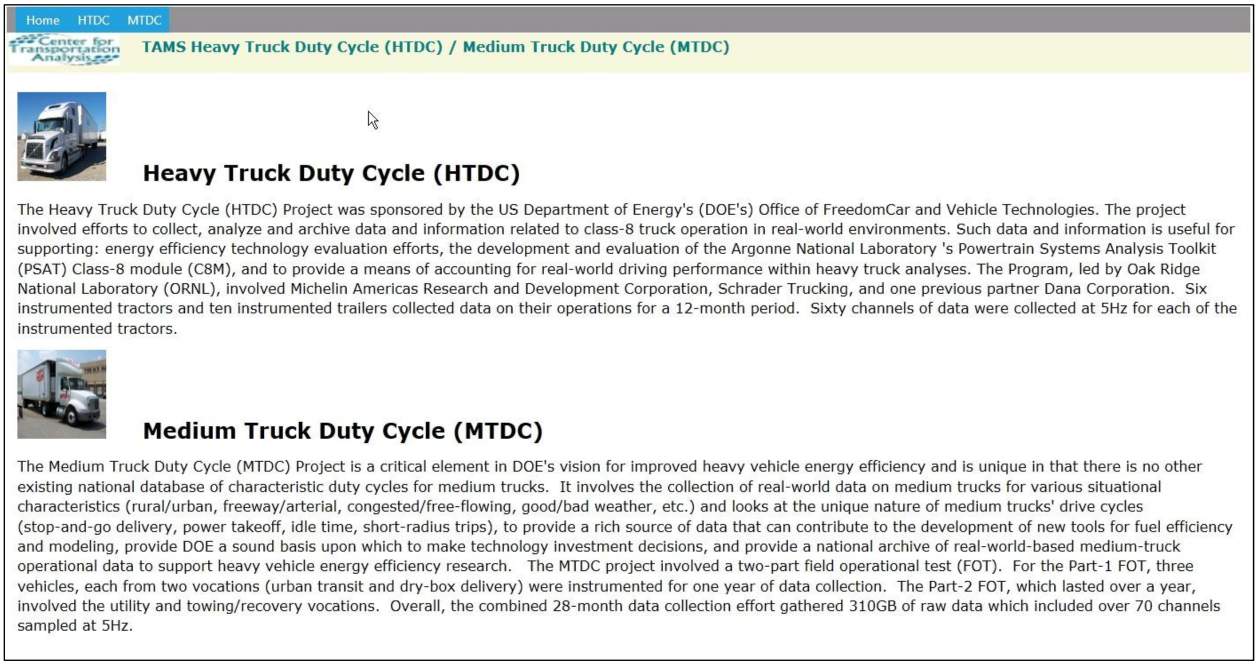
The ORNL-developed software analyzed the collected data for each of these situations, flagging missing or invalid data. This indexing allowed for a very efficient management of the information and was used in the data analysis task to allow for the selection of files that contained only the specific information of interest (e.g., a vehicle traveling in urban areas, during the morning peak hour, during rainy weather). Also, a search engine that uses the index pointers was developed and included with the DCGenT Prototype to help with the identification and retrieval of information that satisfies one or more user-selected criteria simultaneously.

The data analysis section presents more information regarding the Data Extractor and Analysis Tool, since this software was the main tool used to conduct all the analyses presented in this report.

3.5 TRANSPORTATION, ANALYSIS, MODELING AND SIMULATION TOOL

The Transportation Analysis, Modeling, and Simulation (TAMS) tool is a web-based application that allows the user to filter the data based upon user-defined criteria. The user can view the filtered data as a grid, as a chart, or spatially in a map. The user determines which data elements are displayed in the grid and chart. The spatial interface can display one or more days' worth of data for each test vehicle. The HTDC and MTDC data is accessed separately using this tool.

For example, the HTDC home page (Figure 18) describes the HTDC project and the data that was collected during that project. The HTDC web-based application requires the user to login with a valid user name and password. A user must register with the web site and be approved before logging into the application. In addition, each user account is assigned a role that determines the allowed operations (e.g., access to entire database vs. access to a limited subset of the data).



TAMS Heavy Truck Duty Cycle (HTDC) / Medium Truck Duty Cycle (MTDC)

Heavy Truck Duty Cycle (HTDC)

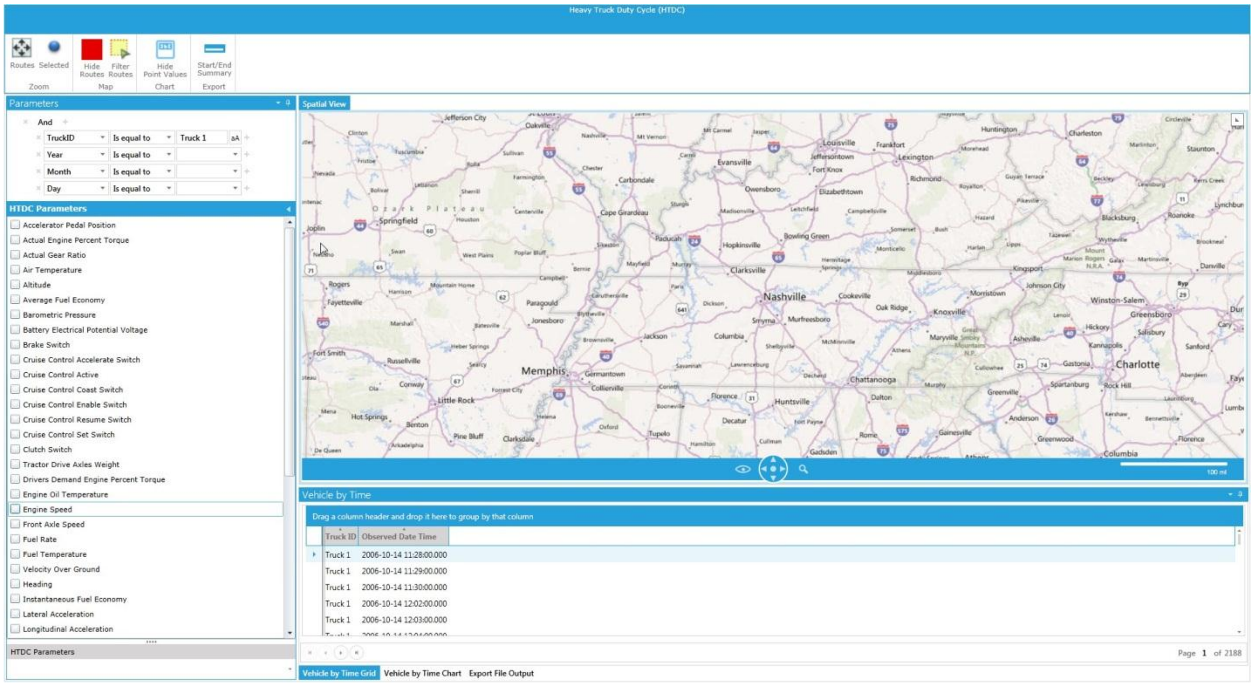
The Heavy Truck Duty Cycle (HTDC) Project was sponsored by the US Department of Energy's (DOE's) Office of FreedomCar and Vehicle Technologies. The project involved efforts to collect, analyze and archive data and information related to class-8 truck operation in real-world environments. Such data and information is useful for supporting: energy efficiency technology evaluation efforts, the development and evaluation of the Argonne National Laboratory 's Powertrain Systems Analysis Toolkit (PSAT) Class-8 module (C8M), and to provide a means of accounting for real-world driving performance within heavy truck analyses. The Program, led by Oak Ridge National Laboratory (ORNL), involved Michelin Americas Research and Development Corporation, Schrader Trucking, and one previous partner Dana Corporation. Six instrumented tractors and ten instrumented trailers collected data on their operations for a 12-month period. Sixty channels of data were collected at 5Hz for each of the instrumented tractors.

Medium Truck Duty Cycle (MTDC)

The Medium Truck Duty Cycle (MTDC) Project is a critical element in DOE's vision for improved heavy vehicle energy efficiency and is unique in that there is no other existing national database of characteristic duty cycles for medium trucks. It involves the collection of real-world data on medium trucks for various situational characteristics (rural/urban, freeway/arterial, congested/free-flowing, good/bad weather, etc.) and looks at the unique nature of medium trucks' drive cycles (stop-and-go delivery, power takeoff, idle time, short-radius trips), to provide a rich source of data that can contribute to the development of new tools for fuel efficiency and modeling, provide DOE a sound basis upon which to make technology investment decisions, and provide a national archive of real-world-based medium-truck operational data to support heavy vehicle energy efficiency research. The MTDC project involved a two-part field operational test (FOT). For the Part-1 FOT, three vehicles, each from two vocations (urban transit and dry-box delivery) were instrumented for one year of data collection. The Part-2 FOT, which lasted over a year, involved the utility and towing/recovery vocations. Overall, the combined 28-month data collection effort gathered 310GB of raw data which included over 70 channels sampled at 5Hz.

Figure 18. TAMS home page.

The data analysis form is displayed after the user has logged into the application. The form has several panels of interest to the user: the filter panel, the parameters panel, the spatial panel, and three data detail panels. The filter panel enables the user to select a subset of the data. The user determines the data of interest by setting the various parameter values. The filter allows the user to combine variables using Boolean operators (i.e., AND/OR). In addition, the user can restrict the variable range using various relational operators (e.g., less than, greater than, and equal to). Figure 19 illustrates the filter operation by setting the TruckID parameter equal to “Truck 1.”

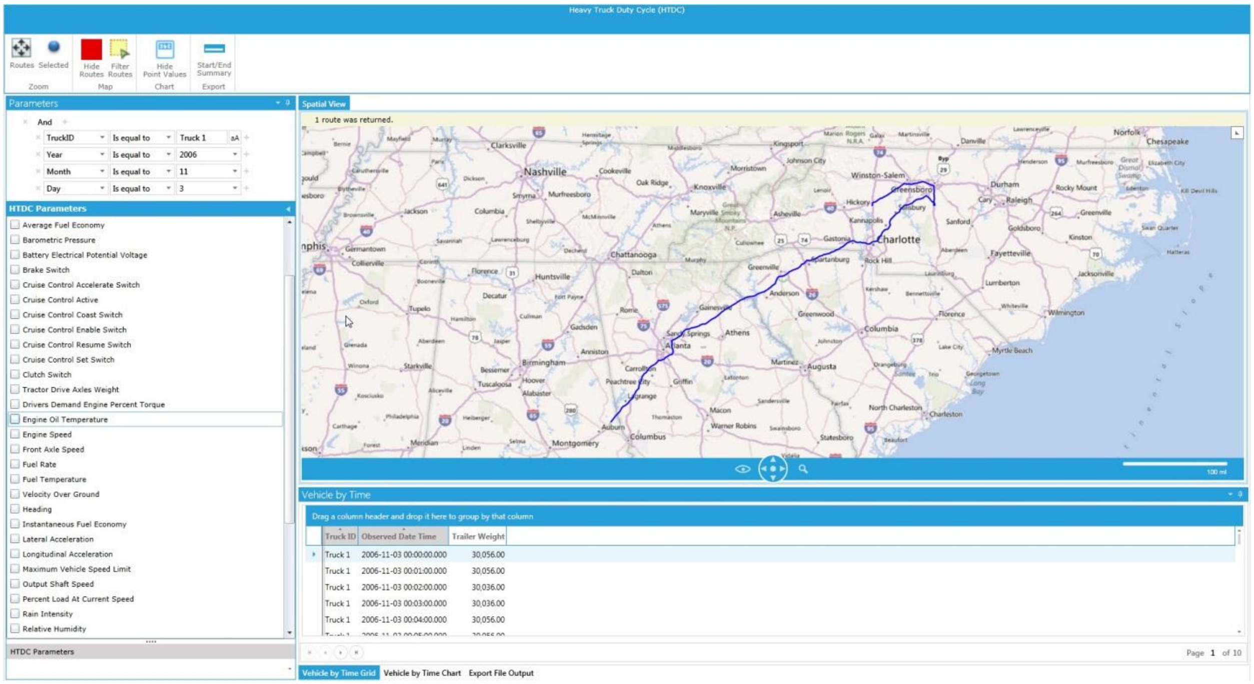


And
TruckID Is equal to Truck 1
Year Is equal to
Month Is equal to
Day Is equal to

Truck ID	Observed Date Time
Truck 1	2006-10-14 11:28:00.000
Truck 1	2006-10-14 11:29:00.000
Truck 1	2006-10-14 11:30:00.000
Truck 1	2006-10-14 12:02:00.000
Truck 1	2006-10-14 12:03:00.000

Figure 19. The application form with filter panel, parameter panel, spatial display, and data details.

Figure 20 shows the result of setting the filter values for TruckID, Year, Month, and Day (Truck 1, November 3, 2006). The user can select one or more parameters from the parameter form. The trailer weight values for the selected truck are displayed in the details form. The spatial display shows the truck route for this set of parameters. The corresponding chart is shown in Figure 21.

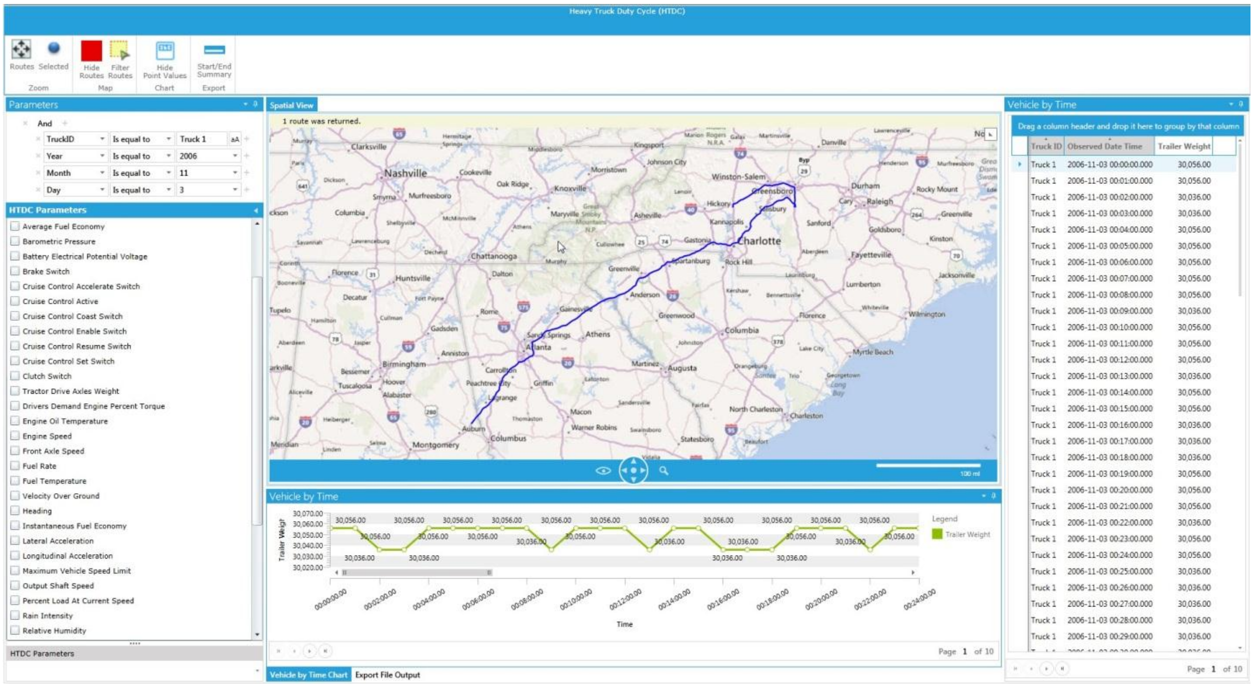


And
TruckID Is equal to Truck 1
Year Is equal to 2006
Month Is equal to 11
Day Is equal to 3

1 route was returned.

Truck ID	Observed Date Time	Trailer Weight
Truck 1	2006-11-03 00:00:00.000	30,056.00
Truck 1	2006-11-03 00:01:00.000	30,056.00
Truck 1	2006-11-03 00:02:00.000	30,036.00
Truck 1	2006-11-03 00:03:00.000	30,036.00
Truck 1	2006-11-03 00:04:00.000	30,056.00

Figure 20 Filter by truck, year, month, and day. The grid in the details form shows the values of the truck, observed date time, and trailer.



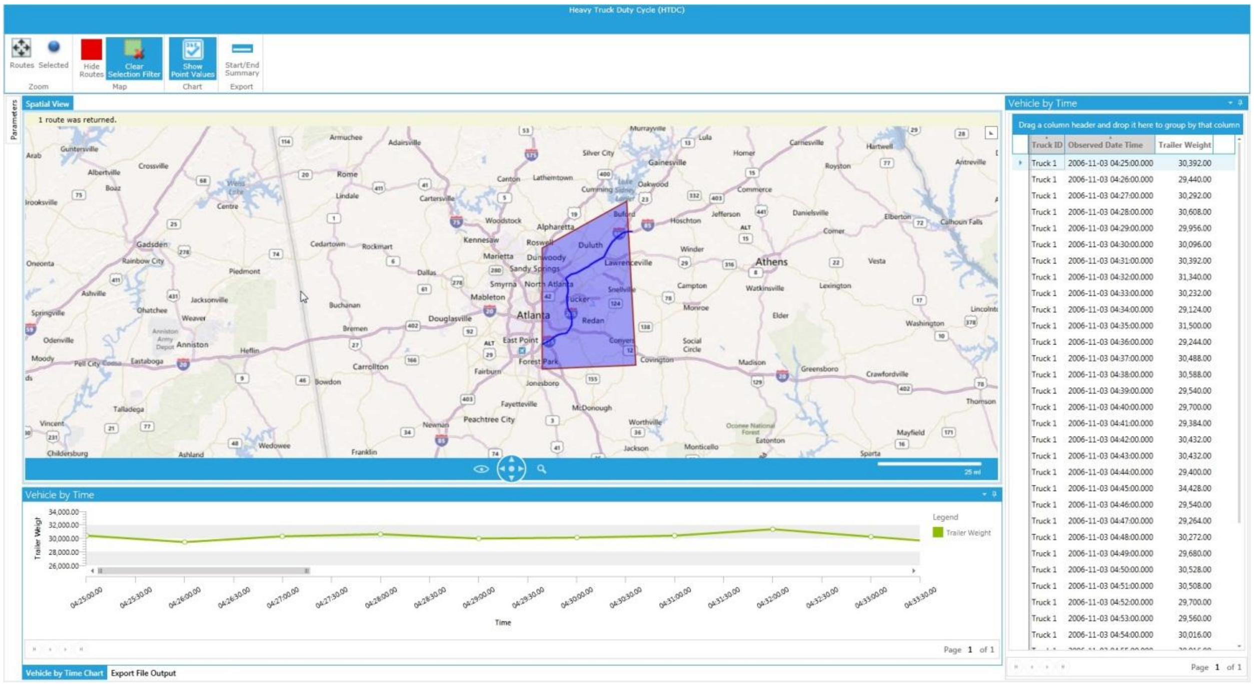
And
TruckID Is equal to Truck 1
Year Is equal to 2006
Month Is equal to 11
Day Is equal to 3

1 route was returned.

Truck ID	Observed Date Time	Trailer Weight
Truck 1	2006-11-03 00:00:00.000	30,056.00
Truck 1	2006-11-03 00:01:00.000	30,056.00
Truck 1	2006-11-03 00:02:00.000	30,036.00
Truck 1	2006-11-03 00:03:00.000	30,036.00
Truck 1	2006-11-03 00:04:00.000	30,056.00
Truck 1	2006-11-03 00:05:00.000	30,056.00
Truck 1	2006-11-03 00:06:00.000	30,056.00
Truck 1	2006-11-03 00:07:00.000	30,056.00
Truck 1	2006-11-03 00:08:00.000	30,056.00
Truck 1	2006-11-03 00:09:00.000	30,036.00
Truck 1	2006-11-03 00:10:00.000	30,056.00
Truck 1	2006-11-03 00:11:00.000	30,056.00
Truck 1	2006-11-03 00:12:00.000	30,056.00
Truck 1	2006-11-03 00:13:00.000	30,036.00
Truck 1	2006-11-03 00:14:00.000	30,056.00
Truck 1	2006-11-03 00:15:00.000	30,056.00
Truck 1	2006-11-03 00:16:00.000	30,036.00
Truck 1	2006-11-03 00:17:00.000	30,036.00
Truck 1	2006-11-03 00:18:00.000	30,036.00
Truck 1	2006-11-03 00:19:00.000	30,056.00
Truck 1	2006-11-03 00:20:00.000	30,056.00
Truck 1	2006-11-03 00:21:00.000	30,056.00
Truck 1	2006-11-03 00:22:00.000	30,036.00
Truck 1	2006-11-03 00:23:00.000	30,056.00
Truck 1	2006-11-03 00:24:00.000	30,056.00
Truck 1	2006-11-03 00:25:00.000	30,036.00
Truck 1	2006-11-03 00:26:00.000	30,036.00
Truck 1	2006-11-03 00:27:00.000	30,036.00
Truck 1	2006-11-03 00:28:00.000	30,036.00
Truck 1	2006-11-03 00:29:00.000	30,036.00

Figure 21. Filter results in chart, grid, and spatial display.

The user can also filter the data using the spatial display. The user defines a bounding box by clicking on the spatial display, and the software extracts the data corresponding to that area. Figure 22 shows the data for a selected area in the grid and chart.



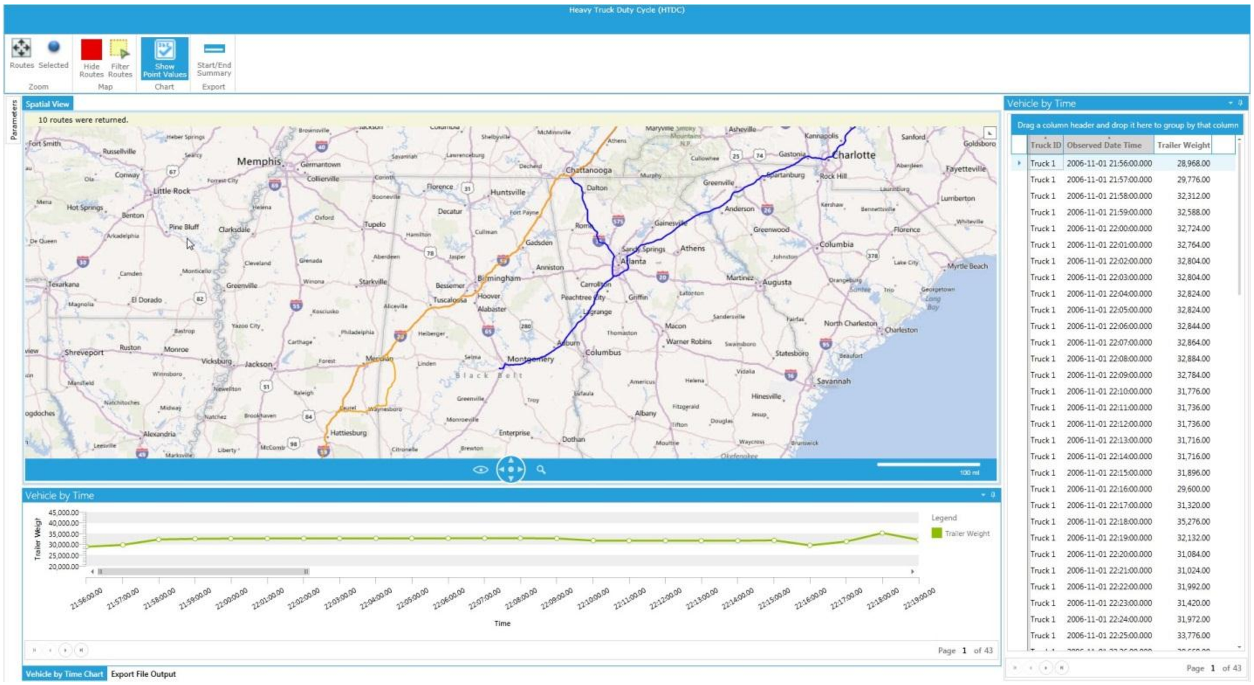
1 route was returned.

Drag a column header and drop it here to group by that column

Truck ID	Observed Date Time	Trailer Weight
Truck 1	2006-11-03 04:25:00.000	30,392.00
Truck 1	2006-11-03 04:26:00.000	29,440.00
Truck 1	2006-11-03 04:27:00.000	30,292.00
Truck 1	2006-11-03 04:28:00.000	30,608.00
Truck 1	2006-11-03 04:29:00.000	29,956.00
Truck 1	2006-11-03 04:30:00.000	30,096.00
Truck 1	2006-11-03 04:31:00.000	30,392.00
Truck 1	2006-11-03 04:32:00.000	31,340.00
Truck 1	2006-11-03 04:33:00.000	30,232.00
Truck 1	2006-11-03 04:34:00.000	29,124.00
Truck 1	2006-11-03 04:35:00.000	31,500.00
Truck 1	2006-11-03 04:36:00.000	29,244.00
Truck 1	2006-11-03 04:37:00.000	30,488.00
Truck 1	2006-11-03 04:38:00.000	30,588.00
Truck 1	2006-11-03 04:39:00.000	29,540.00
Truck 1	2006-11-03 04:40:00.000	29,700.00
Truck 1	2006-11-03 04:41:00.000	29,384.00
Truck 1	2006-11-03 04:42:00.000	30,432.00
Truck 1	2006-11-03 04:43:00.000	30,432.00
Truck 1	2006-11-03 04:44:00.000	29,400.00
Truck 1	2006-11-03 04:45:00.000	34,428.00
Truck 1	2006-11-03 04:46:00.000	29,540.00
Truck 1	2006-11-03 04:47:00.000	29,264.00
Truck 1	2006-11-03 04:48:00.000	30,272.00
Truck 1	2006-11-03 04:49:00.000	29,680.00
Truck 1	2006-11-03 04:50:00.000	30,528.00
Truck 1	2006-11-03 04:51:00.000	30,508.00
Truck 1	2006-11-03 04:52:00.000	29,700.00
Truck 1	2006-11-03 04:53:00.000	29,560.00
Truck 1	2006-11-03 04:54:00.000	30,016.00

Figure 22. Filter by spatial selection.

Figure 23 shows multiple truck routes for a set of filter criteria. The grid and chart show the corresponding values. In addition, the user can group the grid values by truck ID to consolidate the analysis display.



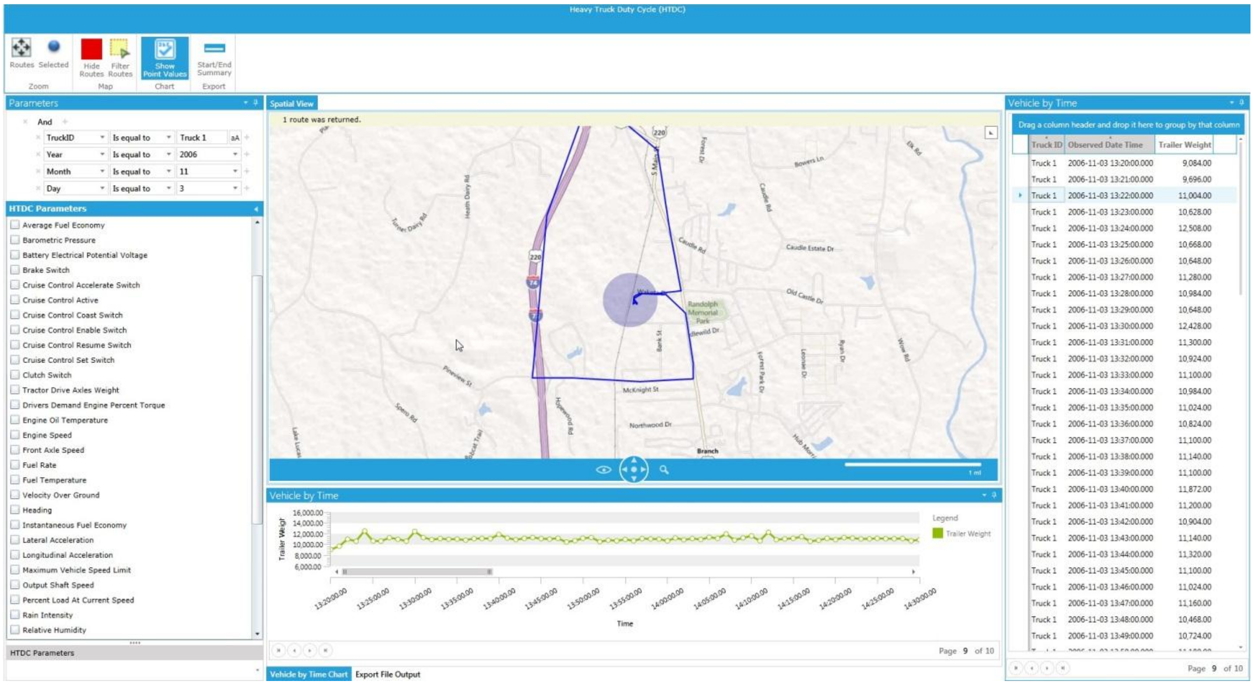
10 routes were returned.

Drag a column header and drop it here to group by that column

Truck ID	Observed Date Time	Trailer Weight
Truck 1	2006-11-01 21:56:00.000	28,968.00
Truck 1	2006-11-01 21:57:00.000	29,776.00
Truck 1	2006-11-01 21:58:00.000	32,312.00
Truck 1	2006-11-01 21:59:00.000	32,588.00
Truck 1	2006-11-01 22:00:00.000	32,724.00
Truck 1	2006-11-01 22:01:00.000	32,764.00
Truck 1	2006-11-01 22:02:00.000	32,804.00
Truck 1	2006-11-01 22:03:00.000	32,804.00
Truck 1	2006-11-01 22:04:00.000	32,824.00
Truck 1	2006-11-01 22:05:00.000	32,824.00
Truck 1	2006-11-01 22:06:00.000	32,844.00
Truck 1	2006-11-01 22:07:00.000	32,864.00
Truck 1	2006-11-01 22:08:00.000	32,884.00
Truck 1	2006-11-01 22:09:00.000	32,784.00
Truck 1	2006-11-01 22:10:00.000	31,776.00
Truck 1	2006-11-01 22:11:00.000	31,736.00
Truck 1	2006-11-01 22:12:00.000	31,736.00
Truck 1	2006-11-01 22:13:00.000	31,716.00
Truck 1	2006-11-01 22:14:00.000	31,716.00
Truck 1	2006-11-01 22:15:00.000	31,896.00
Truck 1	2006-11-01 22:16:00.000	29,600.00
Truck 1	2006-11-01 22:17:00.000	31,320.00
Truck 1	2006-11-01 22:18:00.000	35,276.00
Truck 1	2006-11-01 22:19:00.000	32,132.00
Truck 1	2006-11-01 22:20:00.000	31,084.00
Truck 1	2006-11-01 22:21:00.000	31,024.00
Truck 1	2006-11-01 22:22:00.000	31,992.00
Truck 1	2006-11-01 22:23:00.000	31,420.00
Truck 1	2006-11-01 22:24:00.000	31,972.00
Truck 1	2006-11-01 22:25:00.000	33,776.00

Figure 23. Multiple trucks with multiple routes.

The user can select a point from the grid or chart and zoom to that location (Figure 24) in the spatial display. A summary tooltip will appear if the user moves the mouse over the point. In addition, the user can switch from the map view to an aerial view of the location (see Figure 25).



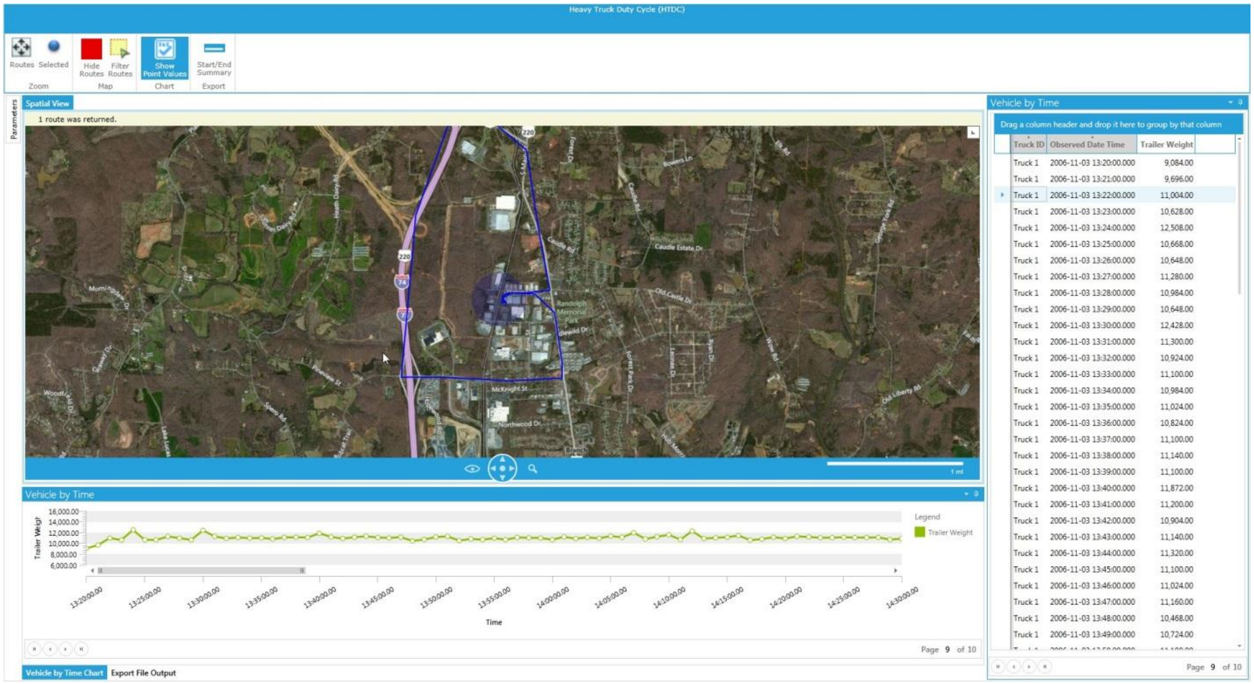
And
TruckID Is equal to Truck 1
Year Is equal to 2006
Month Is equal to 11
Day Is equal to 3

☐ Average Fuel Economy
☐ Barometric Pressure
☐ Battery Electrical Potential Voltage
☐ Brake Switch
☐ Cruise Control Accelerate Switch
☐ Cruise Control Active
☐ Cruise Control Coast Switch
☐ Cruise Control Enable Switch
☐ Cruise Control Resume Switch
☐ Cruise Control Set Switch
☐ Clutch Switch
☐ Tractor Drive Axles Weight
☐ Drivers Demand Engine Percent Torque
☐ Engine Oil Temperature
☐ Engine Speed
☐ Front Axle Speed
☐ Fuel Rate
☐ Fuel Temperature
☐ Velocity Over Ground
☐ Heading
☐ Instantaneous Fuel Economy
☐ Lateral Acceleration
☐ Longitudinal Acceleration
☐ Maximum Vehicle Speed Limit
☐ Output Shaft Speed
☐ Percent Load At Current Speed
☐ Rain Intensity
☐ Relative Humidity

Drag a column header and drop it here to group by that column

Truck ID	Observed Date Time	Trailer Weight
Truck 1	2006-11-03 13:20:00.000	9,084.00
Truck 1	2006-11-03 13:21:00.000	9,696.00
Truck 1	2006-11-03 13:22:00.000	11,004.00
Truck 1	2006-11-03 13:23:00.000	10,628.00
Truck 1	2006-11-03 13:24:00.000	12,508.00
Truck 1	2006-11-03 13:25:00.000	10,668.00
Truck 1	2006-11-03 13:26:00.000	10,648.00
Truck 1	2006-11-03 13:27:00.000	11,280.00
Truck 1	2006-11-03 13:28:00.000	10,984.00
Truck 1	2006-11-03 13:29:00.000	10,648.00
Truck 1	2006-11-03 13:30:00.000	12,428.00
Truck 1	2006-11-03 13:31:00.000	11,300.00
Truck 1	2006-11-03 13:32:00.000	10,924.00
Truck 1	2006-11-03 13:33:00.000	11,100.00
Truck 1	2006-11-03 13:34:00.000	10,984.00
Truck 1	2006-11-03 13:35:00.000	11,024.00
Truck 1	2006-11-03 13:36:00.000	10,824.00
Truck 1	2006-11-03 13:37:00.000	11,100.00
Truck 1	2006-11-03 13:38:00.000	11,140.00
Truck 1	2006-11-03 13:39:00.000	11,100.00
Truck 1	2006-11-03 13:40:00.000	11,872.00
Truck 1	2006-11-03 13:41:00.000	11,200.00
Truck 1	2006-11-03 13:42:00.000	10,904.00
Truck 1	2006-11-03 13:43:00.000	11,140.00
Truck 1	2006-11-03 13:44:00.000	11,320.00
Truck 1	2006-11-03 13:45:00.000	11,100.00
Truck 1	2006-11-03 13:46:00.000	11,024.00
Truck 1	2006-11-03 13:47:00.000	11,160.00
Truck 1	2006-11-03 13:48:00.000	10,468.00
Truck 1	2006-11-03 13:49:00.000	10,724.00

Figure 24. Zoom to point from grid selection.

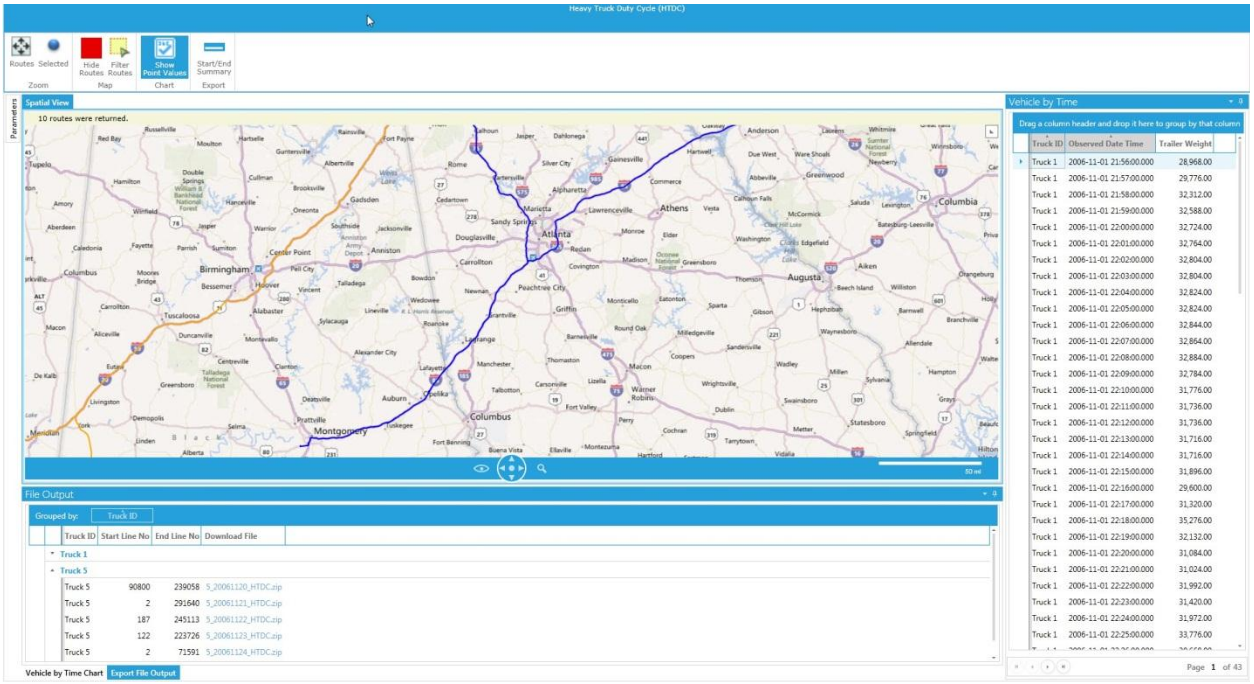


Drag a column header and drop it here to group by that column

Truck ID	Observed Date Time	Trailer Weight
Truck 1	2006-11-03 13:20:00.000	9,084.00
Truck 1	2006-11-03 13:21:00.000	9,696.00
Truck 1	2006-11-03 13:22:00.000	11,004.00
Truck 1	2006-11-03 13:23:00.000	10,628.00
Truck 1	2006-11-03 13:24:00.000	12,508.00
Truck 1	2006-11-03 13:25:00.000	10,668.00
Truck 1	2006-11-03 13:26:00.000	10,648.00
Truck 1	2006-11-03 13:27:00.000	11,280.00
Truck 1	2006-11-03 13:28:00.000	10,984.00
Truck 1	2006-11-03 13:29:00.000	10,648.00
Truck 1	2006-11-03 13:30:00.000	12,428.00
Truck 1	2006-11-03 13:31:00.000	11,300.00
Truck 1	2006-11-03 13:32:00.000	10,924.00
Truck 1	2006-11-03 13:33:00.000	11,100.00
Truck 1	2006-11-03 13:34:00.000	10,984.00
Truck 1	2006-11-03 13:35:00.000	11,024.00
Truck 1	2006-11-03 13:36:00.000	10,824.00
Truck 1	2006-11-03 13:37:00.000	11,100.00
Truck 1	2006-11-03 13:38:00.000	11,140.00
Truck 1	2006-11-03 13:39:00.000	11,100.00
Truck 1	2006-11-03 13:40:00.000	11,872.00
Truck 1	2006-11-03 13:41:00.000	11,200.00
Truck 1	2006-11-03 13:42:00.000	10,904.00
Truck 1	2006-11-03 13:43:00.000	11,140.00
Truck 1	2006-11-03 13:44:00.000	11,320.00
Truck 1	2006-11-03 13:45:00.000	11,100.00
Truck 1	2006-11-03 13:46:00.000	11,024.00
Truck 1	2006-11-03 13:47:00.000	11,160.00
Truck 1	2006-11-03 13:48:00.000	10,468.00
Truck 1	2006-11-03 13:49:00.000	10,724.00

Figure 25. Aerial view of point from grid.

The user can also download the raw data files for the filtered data set. The raw data files contain all of the parameter values that match the user's criteria. Figure 26 shows the data file summary grouped by truck ID. Each row provides a hyperlink from which to download the data file.



Grouped by: Truck ID

Truck ID	Start Line No	End Line No	Download File
Truck 1			
Truck 5			
Truck 5	90800	239058	5_20061120_HTDC.zip
Truck 5	2	291640	5_20061121_HTDC.zip
Truck 5	187	245113	5_20061122_HTDC.zip
Truck 5	122	223726	5_20061123_HTDC.zip
Truck 5	2	71591	5_20061124_HTDC.zip

Truck ID	Observed Date Time	Trailer Weight
Truck 1	2006-11-01 21:56:00.000	28,968.00
Truck 1	2006-11-01 21:57:00.000	29,776.00
Truck 1	2006-11-01 21:58:00.000	32,312.00
Truck 1	2006-11-01 21:59:00.000	32,588.00
Truck 1	2006-11-01 22:00:00.000	32,724.00
Truck 1	2006-11-01 22:01:00.000	32,764.00
Truck 1	2006-11-01 22:02:00.000	32,804.00
Truck 1	2006-11-01 22:03:00.000	32,804.00
Truck 1	2006-11-01 22:04:00.000	32,824.00
Truck 1	2006-11-01 22:05:00.000	32,824.00
Truck 1	2006-11-01 22:06:00.000	32,844.00
Truck 1	2006-11-01 22:07:00.000	32,864.00
Truck 1	2006-11-01 22:08:00.000	32,884.00
Truck 1	2006-11-01 22:09:00.000	32,784.00
Truck 1	2006-11-01 22:10:00.000	31,776.00
Truck 1	2006-11-01 22:11:00.000	31,736.00
Truck 1	2006-11-01 22:12:00.000	31,736.00
Truck 1	2006-11-01 22:13:00.000	31,716.00
Truck 1	2006-11-01 22:14:00.000	31,716.00
Truck 1	2006-11-01 22:15:00.000	31,896.00
Truck 1	2006-11-01 22:16:00.000	29,600.00
Truck 1	2006-11-01 22:17:00.000	31,320.00
Truck 1	2006-11-01 22:18:00.000	35,276.00
Truck 1	2006-11-01 22:19:00.000	32,132.00
Truck 1	2006-11-01 22:20:00.000	31,084.00
Truck 1	2006-11-01 22:21:00.000	31,024.00
Truck 1	2006-11-01 22:22:00.000	31,992.00
Truck 1	2006-11-01 22:23:00.000	31,420.00
Truck 1	2006-11-01 22:24:00.000	31,972.00
Truck 1	2006-11-01 22:25:00.000	33,776.00

Figure 26. Export files from filtered data.

3.6 DUTY CYCLE GENERATION TOOL

Vehicle usage, as characterized by the speeds, accelerations, and roadway grades experienced during travel, plays a primary role in the fuel economy and emissions that a vehicle will achieve. Vehicle performance modeling, using software tools such as Autonomie[9] or GT Drive,[10] provides an effective means to estimate the benefits of a new technology or vehicle configuration on fuel economy or emissions, but the accuracy of the prediction depends on how well the drive cycle used in the analysis matches the actual usage for a given vehicle application. Data measured during normal vehicle operation, such as that collected in the MTDC project, provides an accurate characterization of vehicle usage, and it is highly desirable to use such data as a basis for performance modeling. Long-term test data from multiple vehicles provides the most reliable and statistically meaningful characterization of the usage; however, it would be time-prohibitive to conduct modeling using this complete data set because of its size. It is therefore desirable to generate a synthesis of the original data that can be efficiently used in modeling or testing as a practical substitute for the complete data set. This synthetic duty cycle should be created in such a way that FE results are the same as would be achieved if the complete data set were evaluated.

The Matlab-based Duty Cycle Generation Tool (DCGenT) is a suite of programs designed to generate duty cycles of a practical length for modeling or testing purposes from measured driving data. Large sets of test data can be "compressed" using this tool, which allows researchers to use collected data to perform vehicle simulations and analyses in an efficient manner. With the DCGenT, researchers can now create

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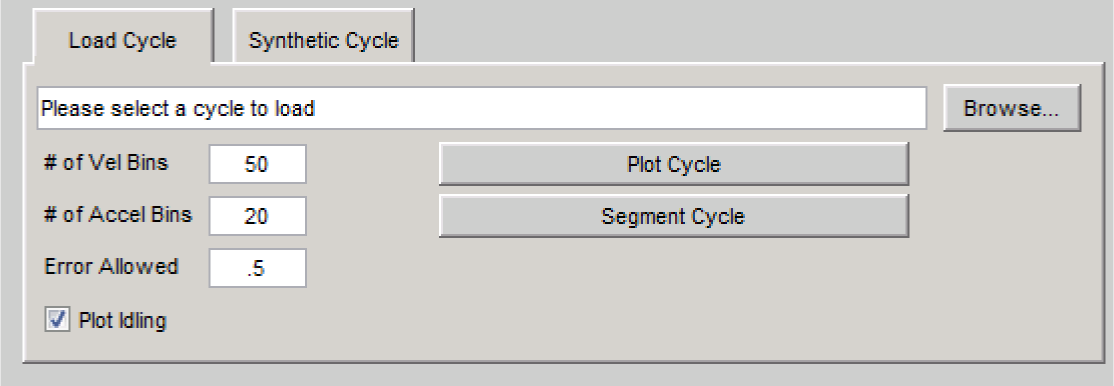
[9] http://www.autonomie.net/.
[10] http://www.gtisoft.com/.

synthetic duty cycles that represent entire days, weeks, or months of data, which will allow more efficiency in data analyses.

The tools in the DCGenT suite rely heavily on the use of bivariate histograms of the speed and acceleration data for creation of the synthetic duty cycle. The histograms characterize the distribution of the accelerations at each speed, giving a concise statistical description of the vehicle usage. The goal of each tool is to duplicate the original histograms as closely as possible in order to match the speed and acceleration characteristics of the original data. Not only are the histograms used for comparison purposes, but also they are the main source of data for calculating and creating the synthetic duty cycles. The tools calculate the synthetic cycle using an iterative procedure until the difference between the histograms of the original and synthetic cycles converges to within a specified error threshold.

The first DCGenT program is a highly automated tool that creates multiple duty cycles using an algorithm-based segmentation of the original duty cycle data. The segments are randomly sampled and the tool chooses a final synthetic cycle based on user-defined error thresholds. In order to use the DCGenT, specific data files are required as inputs that must contain speed data collected at time intervals of 1 s or faster (only 1 Hz data is used for calculations). Elevation data, when present, is also included in defining the synthetic duty cycle, and other data channels such as instantaneous fuel rate, engine RPM, and engine percent torque can be included in the data file since the tool parses and extracts the channels used in the duty cycle creation. Once files have been selected for analysis, users then select the number of histogram bins they want to use and the allowable speed error in segmentation, as shown in Figure 27.



Please select a cycle to load

\# of Vel Bins 50

\# of Accel Bins 20

Error Allowed .5

☑ Plot Idling

Figure 27. Automated DCGenT file load panel.

When a file has been loaded, a plot showing the speed profile is displayed along with the speed and acceleration histogram, as seen in Figure 28.

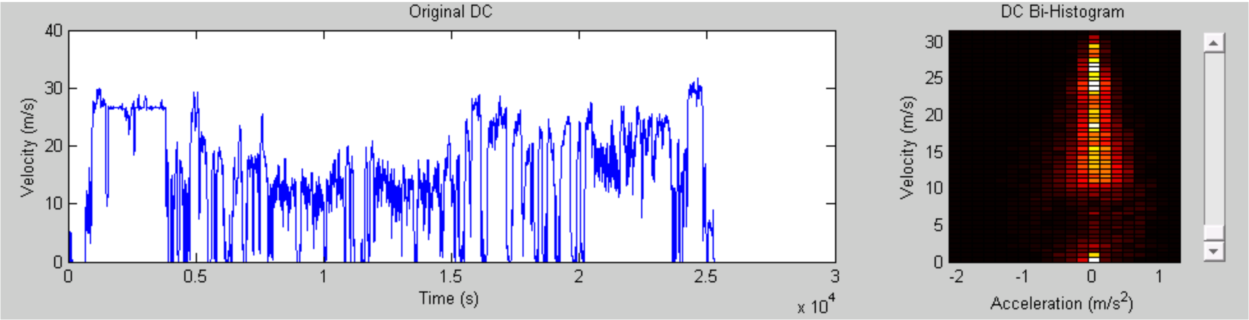


Figure 28. Automated DCGenT imported cycle plot.

When a user has completed loading the data to be analyzed, he/she can then segment the cycle into linear sections that will be used to create the synthetic cycle. To segment the loaded cycle, a modified version of the Douglas-Peucker[11] point reduction algorithm is used to generate the individual segments. Once created, the segments are classified based on characteristics such as idling, acceleration, deceleration, or cruising. The segments are also ordered by average speed and average acceleration. An example of the created segments is shown in an exaggerated form in Figure 29.

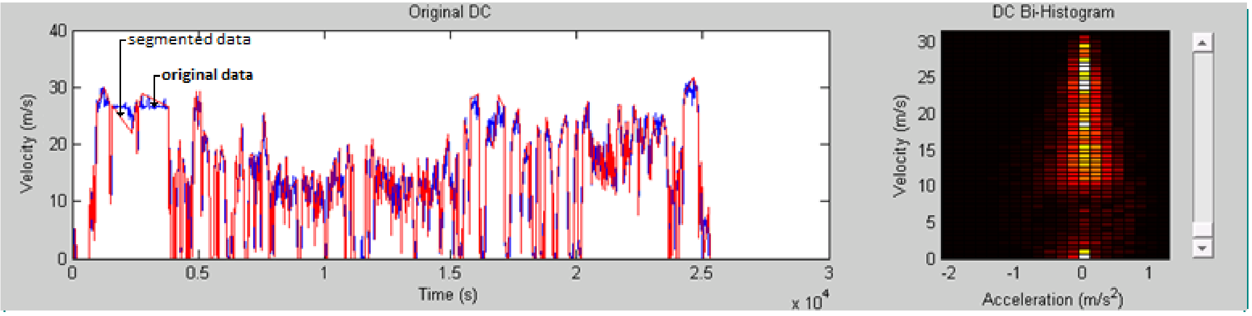
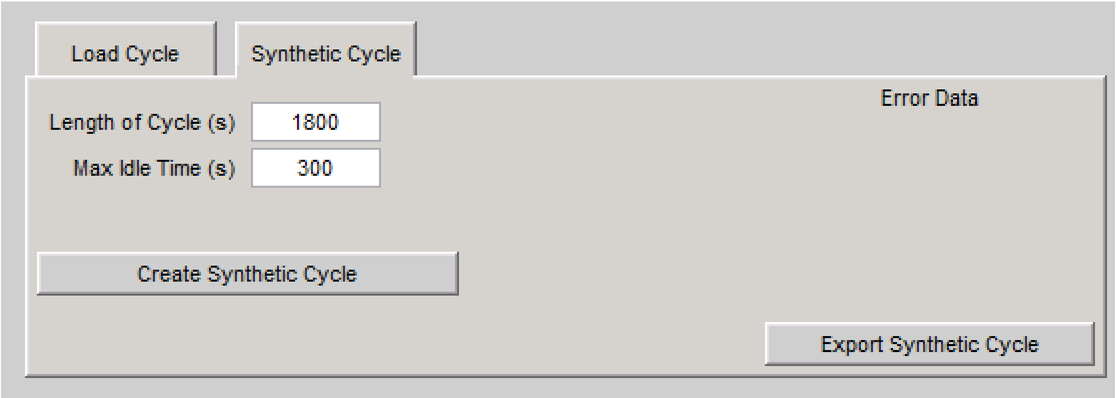


Figure 29. Automated DCGenT segmented cycle plot.

After creating the segments, the user continues to create the synthetic cycle. Using the synthetic cycle panel, the user enters the desired cycle length along with the maximum idle time. The synthetic cycle panel and the resulting representative synthetic cycle are shown in Figure 30 and Figure 31.



Length of Cycle (s) 1800

Max Idle Time (s) 300

Figure 30. Automated DCGenT synthetic cycle panel.

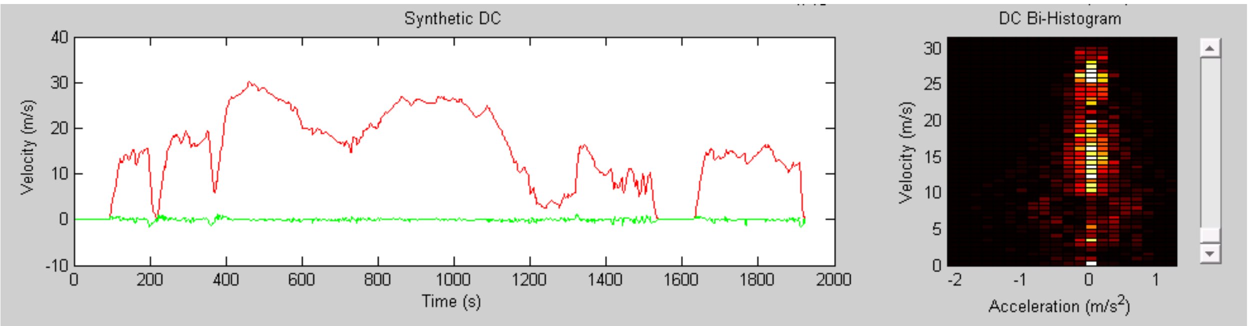


Figure 31. Automated DCGenT synthetic cycle plot.

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[11] David Douglas and Thomas Peucker, “Algorithms for the reduction of the number of points required to represent a digitized line or its caricature,” *The Canadian Cartographer* **10**(2), 112–122 (1973).

Segments are arranged in a specific order with an idling time at the beginning and the end of the cycle. After any idle time, an acceleration segment is then placed, which will bring the speed up to an acceptable level. The bivariate histogram is then sampled from a weighted acceleration histogram for specific cruising segments based on the end speed of the last segment inserted. Once the user-defined cycle length has been reached, the cycle will begin going to zero velocity in order to complete a continuous cycle.

The speed–and acceleration histogram for the synthetic duty cycle will generally not be identical to that of the original cycle. However, the tool displays metrics such as average speed, maximum speed, acceleration times, and deceleration times, which can be compared with the original cycle in addition to comparing the histograms to determine if it is indeed representative. All of the metrics should be within 10% (calculated percentage difference between original and synthetic data) of the original duty cycle to have a reasonably representative synthetic cycle. For the previously shown synthetic cycle, the resulting errors are shown in Table 5.

Table 5. Synthetic Duty Cycle Error Example

Duty cycle metric	Percent error from original data (absolute)
Idle time	6.8063
Average speed	1.5156
Time accelerating	7.4738
Time decelerating	4.1852
Maximum speed	4.7227
Root mean square	3.1197

The automated DCGenT does not always converge to create representative cycles for every type of duty cycle analyzed (for example, cycles with driving predominantly on the freeway are often problematic, because of only slight variations in data), and the computational time to create the synthetic cycle increases significantly when original cycles much longer than a few hours are processed. This limits the practical use of the tool to approximately 1 day's worth of original data or less. (For data comprising multiple days or weeks, the tool can be used to process data from separate days one at a time, and the generated synthetic cycles can be subsequently combined to create a new input cycle that could be reprocessed with the tool.) Nonetheless, for many cycles, this tool allows researchers to very quickly create a representative synthetic duty cycle with low error, enabling efficient analysis of the data.

When more accuracy is desired for the synthetic cycle or for the analysis of larger data sets, there is a more manual version of the automated DCGenT. This version of the tool consists of three separate Matlab-based programs, which use many of the same functions incorporated in the automated DCGenT but rely on the user's judgment to create the synthetic cycle as opposed to having it generated using a purely algorithmic approach. The first program is an interface that allows researchers to load as much data as desired, but data storage is performed in a manner that economizes the required computing resources. Reduction of the data that is stored from each file is necessary for the larger data sets, and the user must select the individual histograms or files to use in later tools and launch the segmentation function only for these files. This was a necessary change from the automated tool, which is rather resource intensive. Typically, histograms that are similar to that of the entire data set are selected in order to make the matching of the histograms more efficient, but the user has full control of the selection process. The histogram interface is shown in Figure 32.

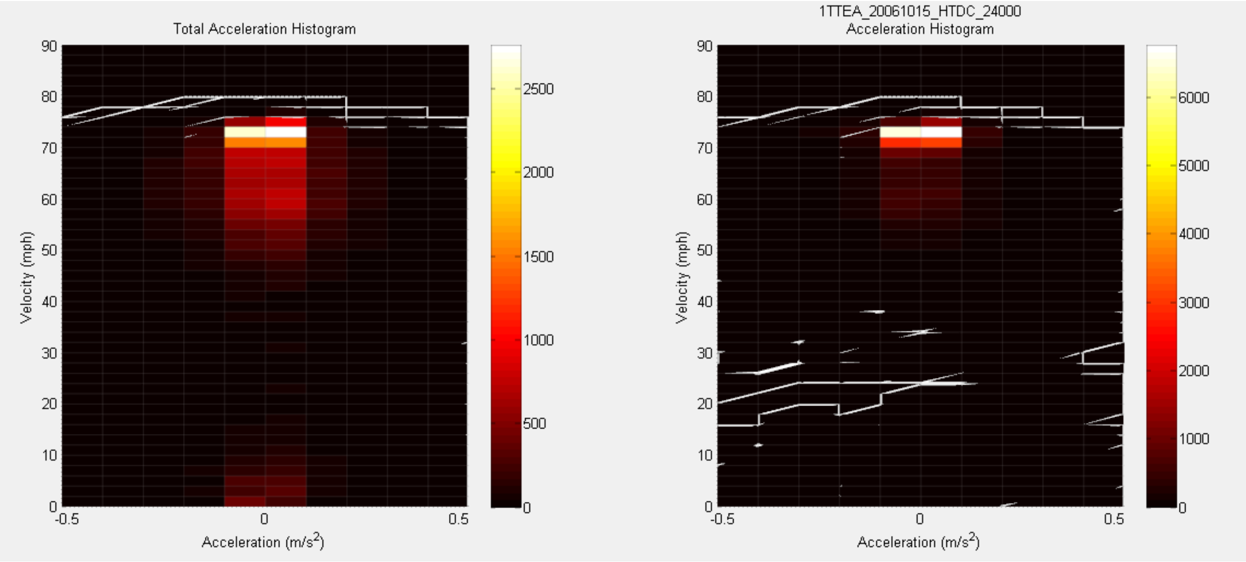


Figure 32. Manual DCGenT file select histograms.

Once the user has selected the desired set of files, the data is processed to create shorter duty cycle segments that are easier to manage in subsequent steps of the synthetic cycle creation. These segments are loaded into the second program, which allows for specific segments to be selected from each file for inclusion in the synthetic cycle. Most of the time spent creating a synthetic cycle using the manual method will be spent within this tool. The user must select segments one at a time in order to generate a synthetic histogram (which is simply an accumulation of the individual segments' histograms) that matches the histogram of the complete data set. The tool manages the accounting of the synthetic histogram as segments are selected and presents a histogram representing the difference between the original data set and the synthetic data. The user's objective when creating the synthetic duty cycle, therefore, is to achieve a difference histogram that approaches zero. The difference histogram and data for an individual segment, as they are presented in the tool during the selection process, are shown in Figure 33. The tool presents the segments in groups during the selection process, as shown in Figure 34.

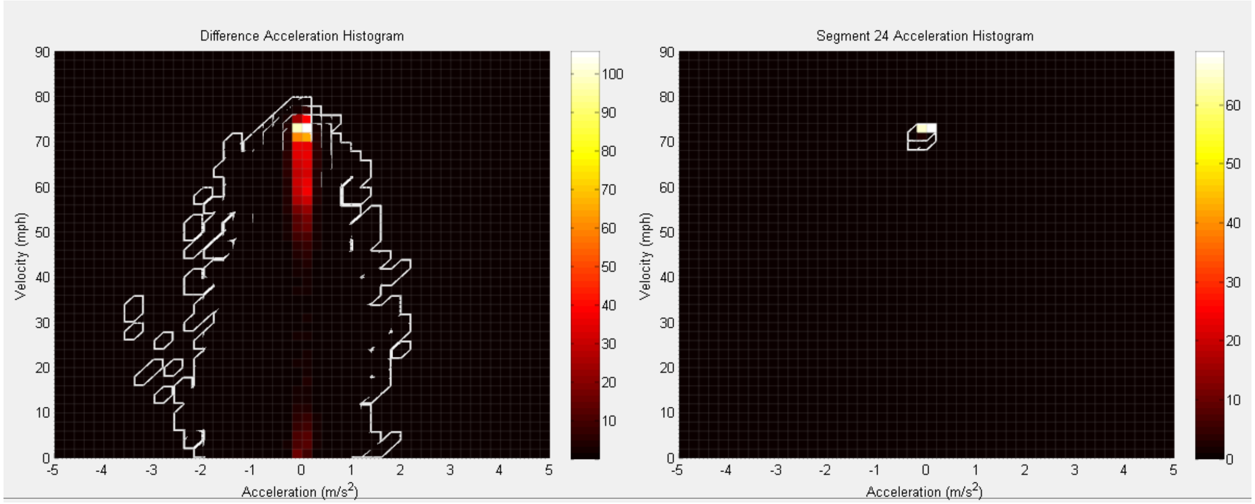


Figure 33. Manual DCGenT file segment histograms.

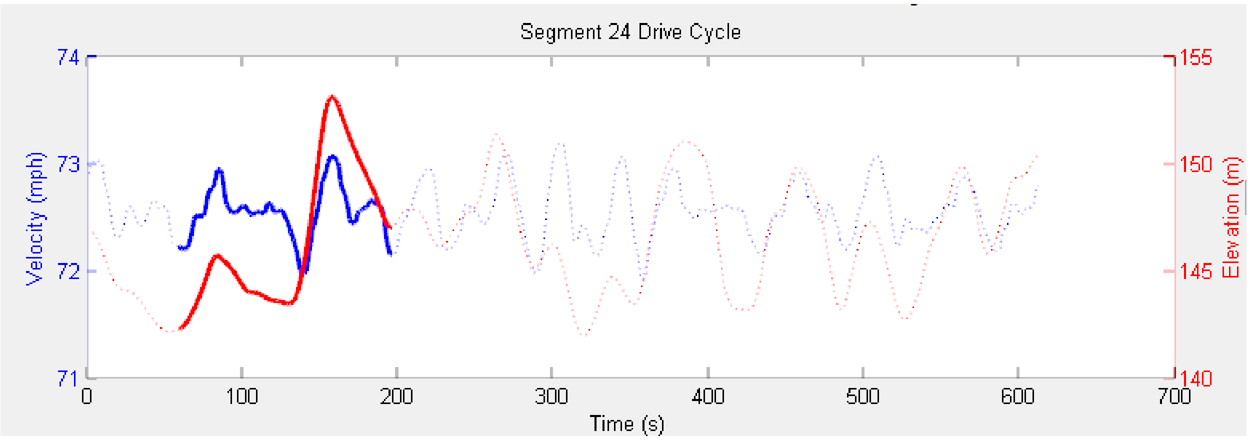
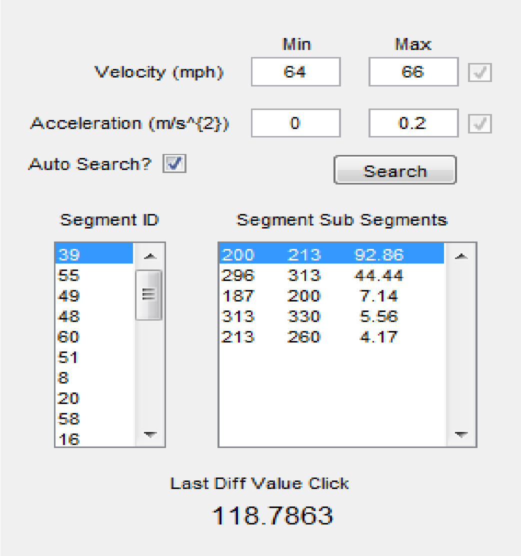


Figure 34. Manual DCGenT segment plot.

Because this can be a rather tedious process, a segment search functionality was implemented in the tool to simplify the identification of segments whose histograms are found to be good candidates for inclusion in the synthetic duty cycle. Generally, finding segments that match the denser bins of the histogram will be the first step in selecting a specific segment. When the user clicks an individual bin on the histogram, a list of segments matching a specified search criterion is displayed along with the length of the identified segments. This search algorithm and some other user-aid functions have proved to make the selection process much more efficient than a purely manual approach. The search interface is shown in Figure 35.



	Min	Max	
Velocity (mph)	64	66	☑
Acceleration (m/s^{2})	0	0.2	☑

Auto Search? ☑

Segment ID
39
55
49
48
60
51
8
20
58
16

Segment Sub Segments

200	213	92.86
296	313	44.44
187	200	7.14
313	330	5.56
213	260	4.17

Last Diff Value Click
118.7863

Figure 35. Manual DCGenT segment search.

After a tentative synthetic histogram is generated that is similar to the original histogram, the third and final program is run. The main goal of this program is to arrange the segments selected in the previous program in sequential order to create the final synthetic duty cycle with continuous and smooth speed and elevation profiles. This is done using a process of matching starting and ending speeds between subsequent segments. The main features of the program include the ability to insert additional data points—for cases in which end points do not match up smoothly, moving entire sections of data easily without having to delete and reinsert segments, scaling histograms without reloading any data, and incorporating measured elevation data, if available, into the final cycle. A nearly complete synthetic cycle is shown in Figure 36.

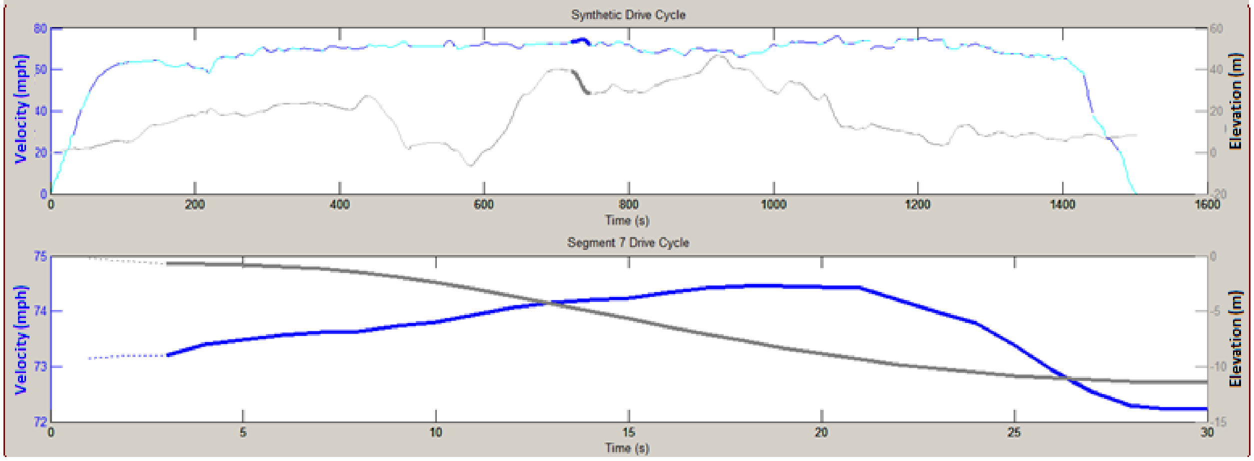
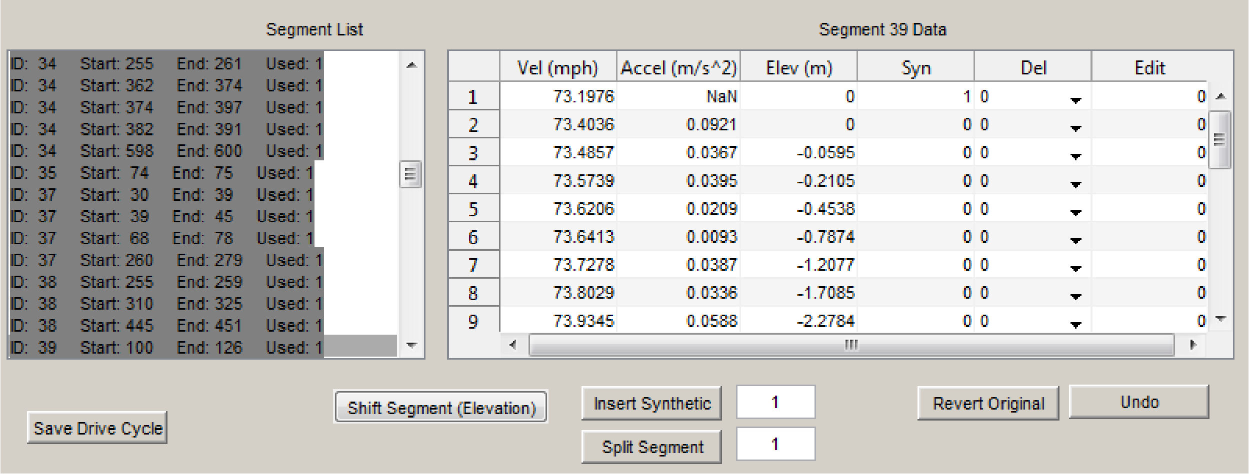


Figure 36. Manually-generated DCGenT synthetic plot.

This cycle, however, contains some data gaps between segments so that the speed is not continuous. To remedy this problem, the user can select the problem segment or segments and move them, or the user may add points to the beginning or end of any segment in order to create the desired continuous cycle. Figure 37 shows the interface used to edit data for any segment.



```
ID:  34    Start: 255    End: 261    Used: 1
ID:  34    Start: 362    End: 374    Used: 1
ID:  34    Start: 374    End: 397    Used: 1
ID:  34    Start: 382    End: 391    Used: 1
ID:  34    Start: 598    End: 600    Used: 1
ID:  35    Start:  74   End:  75   Used: 1
ID:  37    Start:  30   End:  39   Used: 1
ID:  37    Start:  39   End:  45   Used: 1
ID:  37    Start:  68   End:  78   Used: 1
ID:  37    Start: 260    End: 279    Used: 1
ID:  38    Start: 255    End: 259    Used: 1
ID:  38    Start: 310    End: 325    Used: 1
ID:  38    Start: 445    End: 451    Used: 1
ID:  39    Start: 100    End: 126    Used: 1
```

	Vel (mph)	Accel (m/s^2)	Elev (m)	Syn	Del	Edit
1	73.1976	NaN	0	1	0	0
2	73.4036	0.0921	0	0	0	0
3	73.4857	0.0367	-0.0595	0	0	0
4	73.5739	0.0395	-0.2105	0	0	0
5	73.6206	0.0209	-0.4538	0	0	0
6	73.6413	0.0093	-0.7874	0	0	0
7	73.7278	0.0387	-1.2077	0	0	0
8	73.8029	0.0336	-1.7085	0	0	0
9	73.9345	0.0588	-2.2784	0	0	0

Figure 37. Manual DCGenT segment data.

Once all of the segments have been combined for the synthetic cycle, a final synthetic histogram is created which can then be compared with the original data set. The user must make any final adjustments to the synthetic cycle to correct errors in the synthetic histogram that develop during the creation process. As shown in Figure 38, the histogram for the synthetic cycle is nearly identical to the original histogram but in this case, it has a length only about 5% of that of the original duty cycle, which will allow a significant decrease in computation time for use with modeling software.

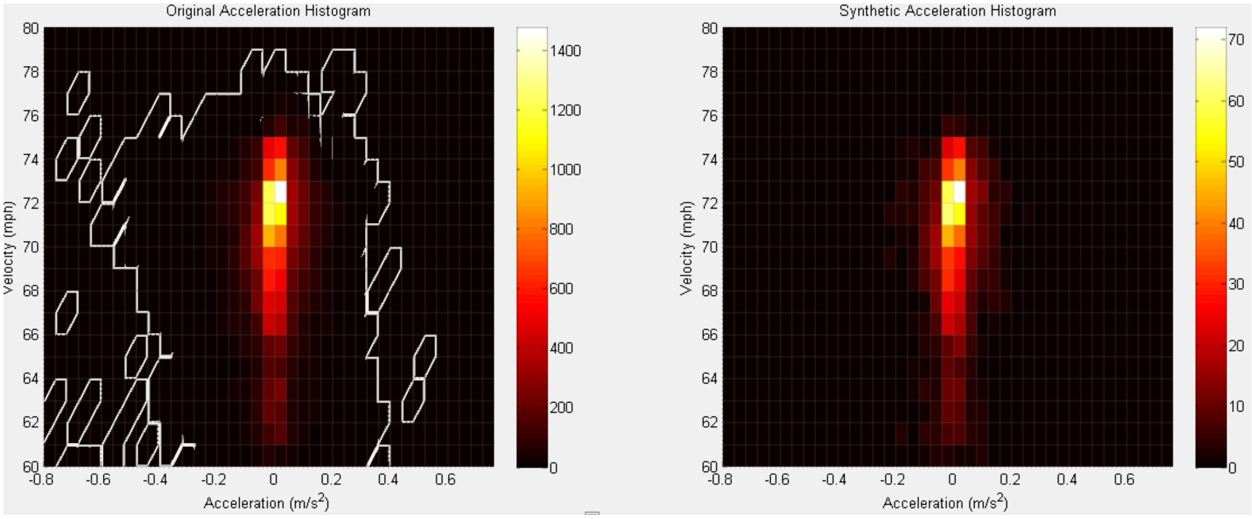


Figure 38. Manual DCGenT synthetic histogram.

Although the manual DCGenT can be used to create highly representative synthetic duty cycles, it does require a significant time commitment to get to the final product. It is important to note that for both versions of the DCGenT, the data points included in the synthetic cycles are extracted directly from the original data, with only a few manually entered points added to make the accelerations smooth and continuous.

Both versions of the DCGenT are capable of creating appropriate-length duty cycle files containing speed and elevation data obtained from measured duty cycle data. The synthetic drive cycle is appropriate for use in tools such as PSAT and Autonomie for modeling vehicle systems. Whereas some vehicle models would require an excessive amount of time to process an original set of even a full day’s worth of data, the DCGenT can be used to create synthetic duty cycles of an appropriate length that can be run significantly faster and will yield the same fuel economy result. Since building hardware can be expensive, the modeling approach using real data is beneficial not only to researchers for testing aerodynamic and other fuel saving technologies without physically instrumenting a vehicle, but also to truck manufacturers and truck fleets for selecting vehicles tuned to their fleets’ specific duty cycles.

4. ANALYSIS OF THE PART 1 FOT DATA

The main goal of the MTDC project was to collect real-world performance and spatial data related to the operations of Class 6, 7, and 8 vehicles from fleets engaged in normal commerce and to provide a means of managing and using the collected data to generate real-world-based duty cycle data and information. In Part 1 of this project, three Class-7 tractors from the HTH fleet and three transit buses from KAT were instrumented, and over 70 channels of data were collected, for a period of over 1 year, at a rate of 5 Hz. The HTH fleet, headquartered in Roane County, Tennessee, operates within an East Tennessee area extending from Cookeville, Tennessee, to the border with North Carolina in the east-west direction, and from the Tennessee–Georgia border to the Tennessee–Kentucky border in the north-south direction (see Figure 39 for spatial coverage of the three trucks that participated in this project). KAT operates in Knoxville, Tennessee, and surrounding areas; Figure 40 shows the routes of the buses participating in this project.

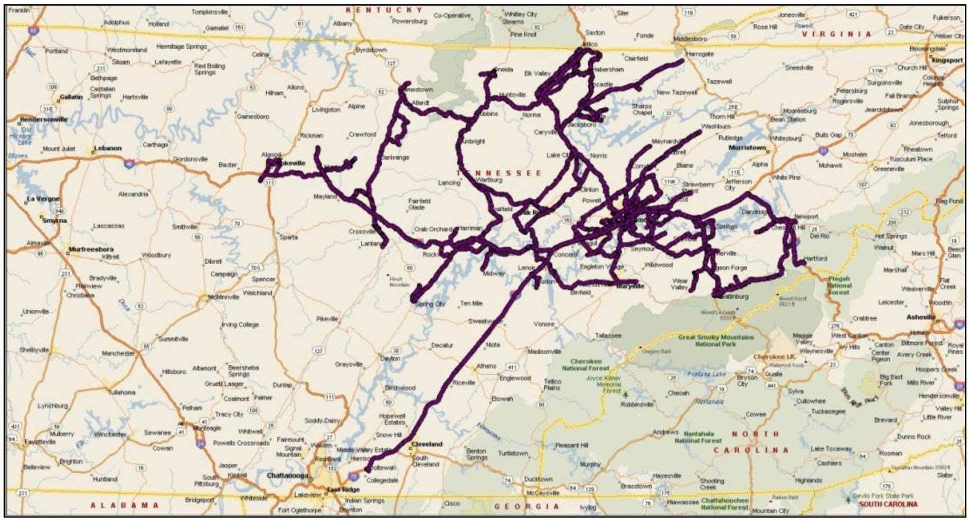


Figure 39. Routes of participating HTH trucks (East Tennessee area).

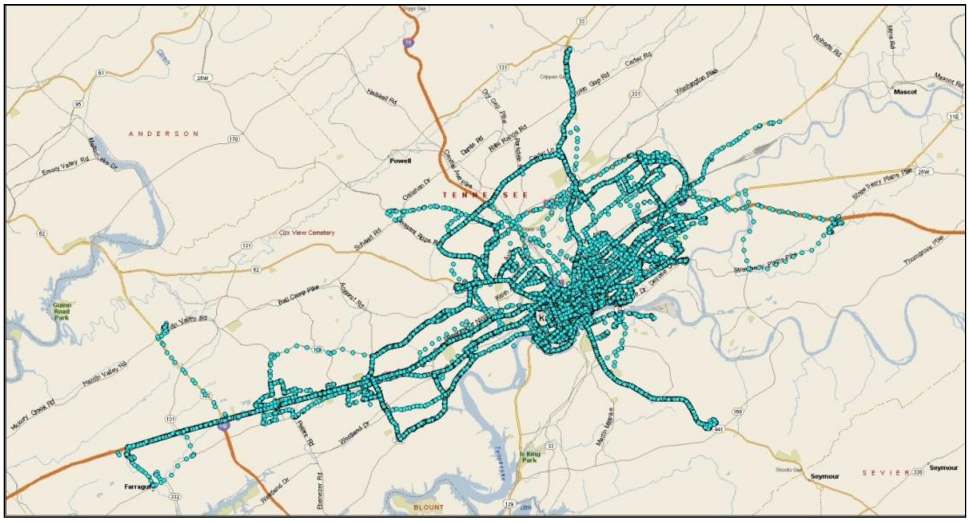


Figure 40. Routes of participating KAT buses (Knoxville, Tennessee, area).

The data gathered in this project included information such as instantaneous fuel rate, engine speed, gear ratio, vehicle speed, and other information read from the vehicle's data bus; spatial information (latitude, longitude, altitude) acquired from a GPS device; and instantaneous tractor (for the combination trucks) and bus weight obtained from devices mounted on the six participating vehicles. Some of the vehicles were also mounted with safety sensors providing brake and tire information. Over the duration of the Part 1 MTDC FOT (just over a year), the three combination trucks traveled nearly 45,500 miles and the three buses logged 49,500 miles.

Section 4 presents the results of an analysis of the data collected in the Part 1 MTDC FOT. Subsection 4.1 describes, in some detail, the data cleansing process and the organization of the extensive information collected in this project. Subsection 4.2 discusses additional models (e.g., a vehicle weight model) developed to complement the collected information. Those models were developed using the data gathered in the project and used to fill gaps for those unusual cases in which a particular channel of information was not collected.

The results of the analysis are then presented, starting with some general statistics and followed by comparisons of the average FEs observed from vehicles operating with different payload levels. A preliminary assessment of duty cycle variability is also presented for both the combination trucks and the transit buses.

The delivery of goods and products required that the combination trucks make many stops at different convenience stores and other points-of-sale to the final consumer. Every day, each one of the vehicles departed from the HTH warehouse and delivered goods and products to 10–20 locations. The driver followed a route of his/her choice to make these deliveries. A study assessing the benefits of using routing software in terms of fuel savings, time savings, and improved safety is presented in this chapter.[12]

4.1 DATA AND ORGANIZATION

The organization and accessibility of the information, as well as its accuracy, play a key role in the quality of any data analysis. Moreover, organization and accessibility of the collected data are particularly important when the size of the information database is significantly large. The field tests conducted as part of this project (more than 70 channels of data collected at 5 Hz for six vehicles) produced a database of 190 GB of uncompressed information (see Table 6 and Table 7).

Table 6. Number and size of data files generated in the project—combination trucks

	MTDC vehicle			Grand total
	1	2	3	
Number of SIF files	179	127	153	459
SIF files total size [GB]	3.78	3.54	3.73	11.05
Number of ASCII files	179	121	149	449
ASCII files total size [GB]	16.27	13.83	15.46	45.56
Number of CSV files*	166	137	150	453
CSV files total size [GB]	5.28	3.95	6.06	15.29

*Comma-separated value files: Files containing the raw data parsed by date.

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[12] This chapter is essentially the same as the one included in the report published by ORNL at the end of Part 1 of the MTDC project (see Franzese et al. ORNL/TM-2010/255), with the following differences: (1) Tables 12, 13, and 15 have been revised; (2) a new subsection with an analysis of the effect of routing software on fuel efficiency and safety has been added to this chapter; and (3) minor typographical corrections and wording clarifications have been made.

Table 7. Number and size of data files generated in the project—transit vehicles

	MTDC vehicle			Grand total
	4	5	6	
Number of SIF files	231	140	226	597
SIF files total size [GB]	13.20	6.23	13.60	33.03
Number of ASCII files	227	137	214	578
ASCII files total size [GB]	59.83	27.37	57.95	145.16
Number of CSV files*	200	150	233	583
CSV files total size [GB]	20.82	6.63	16.09	43.54

*Comma-separated value files: Files containing the raw data parsed by date.

Because of the amount and complexity of the information collected, significant effort was required to prepare the raw data for the analysis. As explained elsewhere in this report, the information was collected using a DAS that saved the information in its proprietary format (i.e., SIF [SoMat Information Files]; SoMat was the manufacturer of the equipment used in the data collection task). These binary files were saved using a data structure format that optimizes the size and accessibility of the information. The information stored in this proprietary format was exported by means of software developed by ORNL to a flat text (i.e., ASCII) format that is readable by any user.

For the Part 1 MTDC FOT, ORNL developed additional software that allowed the retrieval of the information collected "over the air." The protocol used to save the information collected by the instrumented vehicles was as follows. Every night (8:00 p.m. to 12:00 a.m. for the combination trucks, and 1:00 to 5:00 a.m. for the transit buses) the ORNL data retrieval software contacted each vehicle and retrieved the SIF with the information collected during that particular day. The day-long SIF were then translated into an easily readable format as explained above, and the information was parsed into the 70+ channels that were collected and saved to files storing a day's worth of collected data. These files were named with the calendar date on which the data was collected (e.g., 20091113, for information collected on November 13, 2009), plus a one-digit identifier that identified the truck to which the information pertains (1 to 6), and saved as a comma-separated values (CSV) file, a type of ASCII format.

Simultaneous with the formatting of the information from binary to ASCII (and CSV), the software developed by ORNL also checked the validity of the data provided by the 70+ channels. There were instances in which the onboard sensors did not provide information because of, for example, a sensor malfunction ("sensor invalid data"), and other cases in which the DAS had problems storing the data ("eDAQ invalid data"). Each channel had a numeric code that identified these types of problems, and those codes were stored in the file for that particular channel and record. The data cleansing software read this information and generated statistics that were automatically emailed every morning by the software to the ORNL researchers responsible for the data collection effort. This information allowed the researchers to determine when a certain sensor was systematically failing or when the failures were just "glitches" that occurred sporadically. In the first case, troubleshooting, repair/replacement of the particular sensor was accomplished as soon as was feasible.

Other errors such as out-of-range errors and errors attributed to the GPS were also identified, and indications of their occurrence were added to the summary reports. Any record that had any kind of error for any channel was marked with a code that allowed for the identification of those errors, and this information was added to the corresponding calendar date file as a new field.

4.1.1 Spatial Information

The spatial location provided by the onboard GPS (i.e., latitude, longitude, and altitude collected every 0.2 s) permitted the ORNL-developed software to determine the road classification (e.g., freeway) and identification (e.g., I-40) on which the vehicle was traveling, whether it was traveling inside or outside an urban area, and the state in which the truck was located.

Determining the road the truck was traveling was not an easy task, especially since databases with this type of information are not readily available. In a normal geo-coding procedure, a given spatial feature (e.g., a segment of roadway) is represented by a series of points defined by latitude, longitude, and sometimes altitude; and the attributes of that spatial feature (e.g., name of roadway, its classification, number of lanes) associated with these points. This information, kept in proprietary databases, is used by GIS software to draw these features on a map so that when a coordinate is entered (e.g., the location of a truck as determined by the latitude and longitude provided by the onboard GPS device), it could be displayed by placing a symbol of some sort on its actual location (e.g., the off-ramp from eastbound I-75 at Exit 374 in Knoxville, Tennessee). A reverse geo-coding procedure is the process of finding the attributes of a certain feature given the latitude and longitude information of a given point within that feature. That is, for this project, it was necessary to find the classification and name of a given roadway once a point on or very close to that roadway was known. These points were obtained from the onboard GPS devices as the vehicles traveled and therefore were known. Software was written to determine the name and classification of a given spatial feature (roadways in this case) when a latitude-longitude point was provided. The information collected in this way was added to the database of channels, data errors, and spatial information (city and state) described previously prior to archival.

4.1.2 Vehicle Weight Information

In any study involving vehicle FE, weight plays a key role. It was therefore paramount that this type of information be collected in this study. To do so, an Air-Weigh device (described elsewhere in this report) was mounted on the three participating tractors and the three transit buses. They provided instantaneous weight measurements at the steer and drive axles,[13] which were saved as two of the 70+ DAS data channels. The Air-Weigh device was not mounted on any of the HTH trailers. Based on vehicle weight data collected at certified scales (commercial motor vehicle, or CMV, inspection stations in Knox County, Tennessee), ORNL developed a model that predicted the trailer weight based on the tractor weight provided by the Air-Weigh device and vehicle acceleration patterns. This model, described in detail later in this report, was used to assign trailer weight to each one of the records in the database collected in this project. For the transit buses, the deployed Air-Weigh devices provided weight information for the entire vehicle; therefore, it was not necessary to develop a payload estimation model in this case.

4.1.3 Additional Information

Additional information relevant to the data analysis task was also generated and added to the database established in this project. This included roadway slope (in percentages), which was computed using the altitude data gathered with the help of the GPS device, and filtered to smooth out local fluctuations due to GPS errors; and filtered vehicle speed, which was later used to determine acceleration, deceleration, and constant speed intervals.[14] The filter used was a sliding exponential smoothing filter that considered the median of 11 observations before and 11 after the current point.

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[13] The Air-Weigh device uses inputs from the vehicle air-suspension system. For the tractor, only the drive axle weight is measured; the steer axle weight is computed by the Air-Weigh device.

[14] Filtering was needed because of the inherent fluctuations in the data which, if not filtered, would have introduced errors into the data analyses.

4.1.4 Information Indexing

To efficiently find and retrieve specific information from the large database of information collected in this project (i.e., 190 GB) it was necessary to index the information and to create a database of pointers to allow for the quick retrieval of data records that comply with possibly multiple search criteria specified by the analyst.

Several aspects of the collected information were expected to play a relevant role in the data analysis; for example, the following situations were explored:

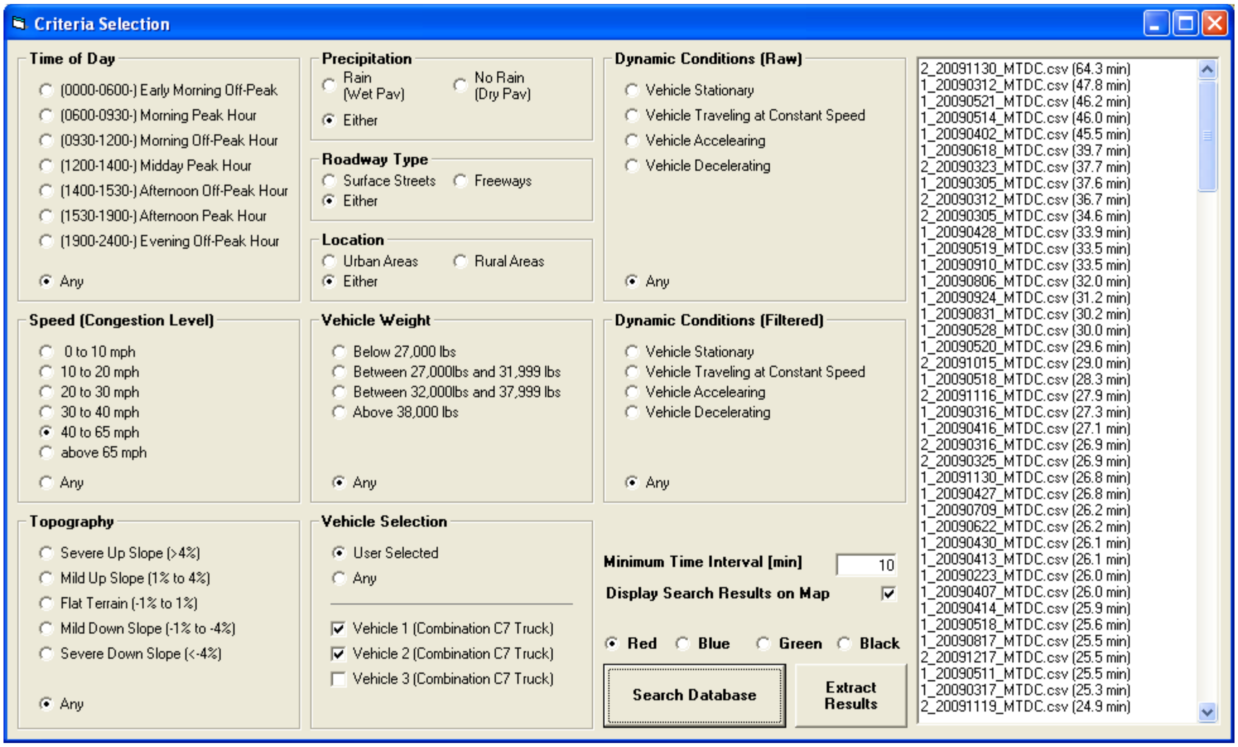
- a vehicle moving on a freeway vs. on a surface street,
- a vehicle moving in an urban area vs. in a rural area,
- a vehicle moving under rainy conditions vs. under clear weather,
- a vehicle moving during the morning peak hour vs. during mid-morning off-peak hours, and
- a vehicle moving vs. one in a stationary position.

For these situations, the ORNL-developed software identified, within the daily data files previously generated, the records in which each attribute is valid or is not valid. This indexing allowed for efficient management of the information and was used in the data analysis task to allow for the selection of files that contained only the specific information of interest (for example, a vehicle traveling in urban areas, during the morning peak hour, and during rainy weather).

A search engine that uses the index pointers was developed by ORNL and included with the DCGenT prototype to help with identifying and retrieving information that satisfies one or more user-selected criteria simultaneously. This newly collected information was added to the already existing HTDC database and made available to the user through a menu choice that allows selecting information about Class-8 trucks, mid-size combination trucks, or transit buses (see Figure 41). Figure 42 and Figure 43 show screen captures of the data selection criteria that are part of the DCGenT prototype for the combination trucks and transit buses, respectively. Those criteria include the following:

1. time of day (peak and off-peak periods),
2. precipitation (indicated by wiper status),
3. roadway type (freeways or surface streets),
4. spatial location (urban or rural areas),
5. congestion level based on vehicle speed and road type,
6. topography (different types of terrain from up slope to flat to down slope),
7. specific vehicle (one or more of the three instrumented tractors or the three instrumented buses),
8. vehicle dynamic condition (e.g., truck stationary, truck accelerating), and
9. vehicle weight (in four levels: empty, light load, medium load, and heavy load.

Figure 41. Vehicle class and vocation selection menu.



Time of Day
○ (0000-0600-) Early Morning Off-Peak
○ (0600-0930-) Morning Peak Hour
○ (0930-1200-) Morning Off-Peak Hour
○ (1200-1400-) Midday Peak Hour
○ (1400-1530-) Afternoon Off-Peak Hour
○ (1530-1900-) Afternoon Peak Hour
○ (1900-2400-) Evening Off-Peak Hour
● Any

Precipitation
○ Rain (Wet Pav) ○ No Rain (Dry Pav)
● Either

Roadway Type
○ Surface Streets ○ Freeways
● Either

Location
○ Urban Areas ○ Rural Areas
● Either

Dynamic Conditions (Raw)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

Speed (Congestion Level)
○ 0 to 10 mph
○ 10 to 20 mph
○ 20 to 30 mph
○ 30 to 40 mph
● 40 to 65 mph
○ above 65 mph
○ Any

Vehicle Weight
○ Below 27,000 lbs
○ Between 27,000lbs and 31,999 lbs
○ Between 32,000lbs and 37,999 lbs
○ Above 38,000 lbs
● Any

Dynamic Conditions (Filtered)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

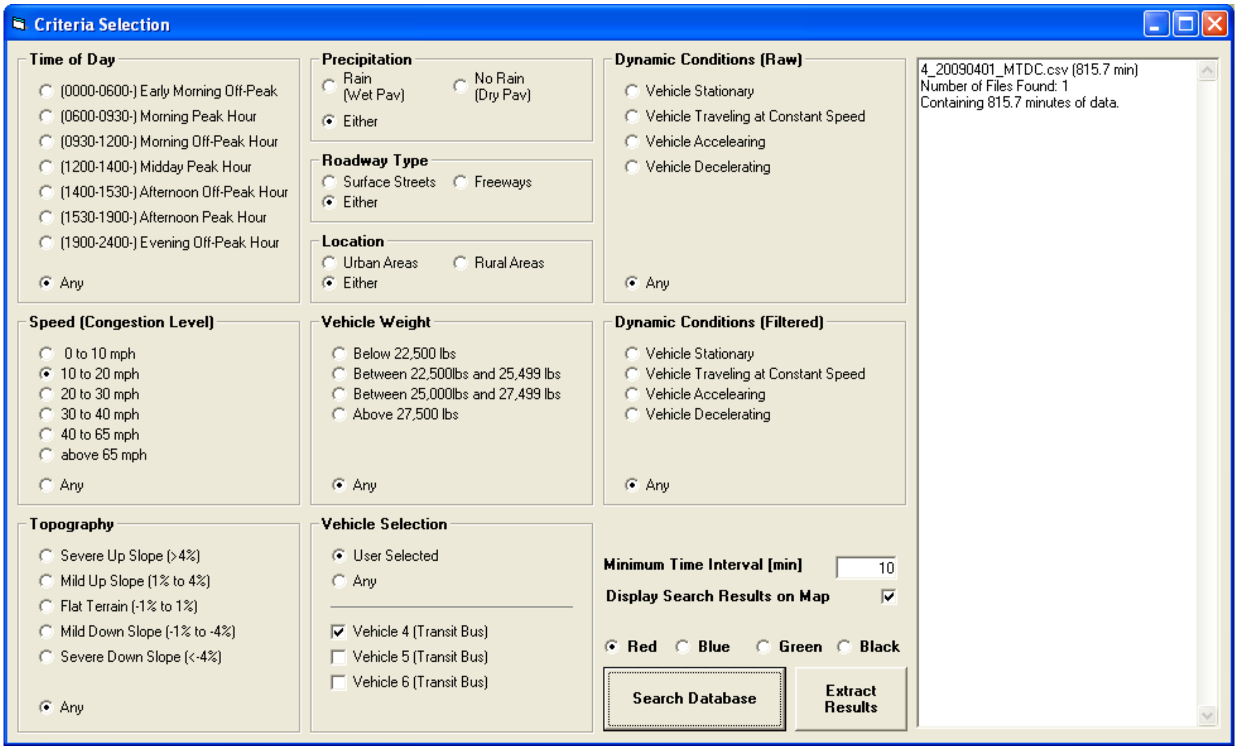
Topography
○ Severe Up Slope (>4%)
○ Mild Up Slope (1% to 4%)
○ Flat Terrain (-1% to 1%)
○ Mild Down Slope (-1% to -4%)
○ Severe Down Slope (<-4%)
● Any

Vehicle Selection
● User Selected
○ Any
☑ Vehicle 1 (Combination C7 Truck)
☑ Vehicle 2 (Combination C7 Truck)
☐ Vehicle 3 (Combination C7 Truck)

Minimum Time Interval [min] 10
Display Search Results on Map ☑
● Red ○ Blue ○ Green ○ Black

```
2_20091130_MTDC.csv (64.3 min)
1_20090312_MTDC.csv (47.8 min)
1_20090521_MTDC.csv (46.2 min)
1_20090514_MTDC.csv (46.0 min)
1_20090402_MTDC.csv (45.5 min)
1_20090618_MTDC.csv (39.7 min)
2_20090323_MTDC.csv (37.7 min)
1_20090305_MTDC.csv (37.6 min)
2_20090312_MTDC.csv (36.7 min)
2_20090305_MTDC.csv (34.6 min)
1_20090428_MTDC.csv (33.9 min)
1_20090519_MTDC.csv (33.5 min)
1_20090910_MTDC.csv (33.5 min)
1_20090806_MTDC.csv (32.0 min)
1_20090924_MTDC.csv (31.2 min)
1_20090831_MTDC.csv (30.2 min)
1_20090528_MTDC.csv (30.0 min)
1_20090520_MTDC.csv (29.6 min)
2_20091015_MTDC.csv (29.0 min)
1_20090518_MTDC.csv (28.3 min)
2_20091116_MTDC.csv (27.9 min)
1_20090316_MTDC.csv (27.3 min)
1_20090416_MTDC.csv (27.1 min)
2_20090316_MTDC.csv (26.9 min)
2_20090325_MTDC.csv (26.9 min)
1_20091130_MTDC.csv (26.8 min)
1_20090427_MTDC.csv (26.8 min)
1_20090709_MTDC.csv (26.2 min)
1_20090622_MTDC.csv (26.2 min)
1_20090430_MTDC.csv (26.1 min)
1_20090413_MTDC.csv (26.1 min)
1_20090223_MTDC.csv (26.0 min)
1_20090407_MTDC.csv (26.0 min)
1_20090414_MTDC.csv (25.9 min)
1_20090518_MTDC.csv (25.6 min)
1_20090817_MTDC.csv (25.5 min)
2_20091217_MTDC.csv (25.5 min)
1_20090511_MTDC.csv (25.5 min)
1_20090317_MTDC.csv (25.3 min)
2_20091119_MTDC.csv (24.9 min)
```

Figure 42. Criteria selection—Class-7 combination trucks.



Time of Day
○ (0000-0600-) Early Morning Off-Peak
○ (0600-0930-) Morning Peak Hour
○ (0930-1200-) Morning Off-Peak Hour
○ (1200-1400-) Midday Peak Hour
○ (1400-1530-) Afternoon Off-Peak Hour
○ (1530-1900-) Afternoon Peak Hour
○ (1900-2400-) Evening Off-Peak Hour
● Any

Precipitation
○ Rain (Wet Pav) ○ No Rain (Dry Pav)
● Either

Roadway Type
○ Surface Streets ○ Freeways
● Either

Location
○ Urban Areas ○ Rural Areas
● Either

Dynamic Conditions (Raw)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

Speed (Congestion Level)
○ 0 to 10 mph
● 10 to 20 mph
○ 20 to 30 mph
○ 30 to 40 mph
○ 40 to 65 mph
○ above 65 mph
○ Any

Vehicle Weight
○ Below 22,500 lbs
○ Between 22,500lbs and 25,499 lbs
○ Between 25,000lbs and 27,499 lbs
○ Above 27,500 lbs
● Any

Dynamic Conditions (Filtered)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

Topography
○ Severe Up Slope (>4%)
○ Mild Up Slope (1% to 4%)
○ Flat Terrain (-1% to 1%)
○ Mild Down Slope (-1% to -4%)
○ Severe Down Slope (<-4%)
● Any

Vehicle Selection
● User Selected
○ Any
☑ Vehicle 4 (Transit Bus)
☐ Vehicle 5 (Transit Bus)
☐ Vehicle 6 (Transit Bus)

Minimum Time Interval [min] 10
Display Search Results on Map ☑
● Red ○ Blue ○ Green ○ Black

```
4_20090401_MTDC.csv (815.7 min)
Number of Files Found: 1
Containing 815.7 minutes of data.
```

Figure 43. Criteria selection—Class-7 transit buses.

After the user has selected all of the searching criteria of interest and the *Search Database* button is pressed, the software finds the list of pointers for the chosen criteria and retrieves from the database all of the records that satisfy these criteria simultaneously.

4.2 ADDITIONAL MODELS DEVELOPED AND DATA CALIBRATION

4.2.1 Vehicle Weight Model

As discussed briefly in the last section, none of the participating trailers was instrumented with Air-Weigh devices; therefore, a truck's total weigh information could not be directly assessed. Past research experience with HTDC has shown that instrumenting trailers for drop-and-hook operations is not cost-effective for the minimal data that can be collected. A truck total-weight-prediction model was developed that used the tractor weight, which was always available, total vehicle weight information obtained at certified CMV scales, and physics related to inertia. That is, as a truck accelerates, the weight of the trailer would resist the change in speed by inducing a force proportional to that weight. This force would impede the movement of the tractor and would appear as a loss of weight as registered by the Air-Weigh device on the tractor, which determines axle weight by sampling the pressure of the air suspension system. Therefore, by observing the behavior (i.e., the weight readings provided by the Air-Weigh device) of the instrumented tractor under different acceleration levels and for known vehicle weights (as obtained from CMV scales), it would be possible, in theory, to characterize the tractor's and trailer's response for a particular payload. A parametric study of payload weights would theoretically provide a truck response map that can be used to estimate the payload weight of tractors mated to uninstrumented trailers.

This theory was tested using vehicle dynamics and tractor weight information collected for the cases in the database in which the vehicle total weight was known from external sources. The tractor weight was sampled within pre-specified acceleration intervals, ranging from -1.4 to 1.4 m/s^2, and linear regression models[15] were developed to fit the "loss of weight" observed as a function of the vehicle acceleration. Figure 44 and Figure 45 show a representation of the tractor weight as a function of vehicle acceleration for a loaded truck (i.e., a truck leaving the warehouse at the beginning of the day) and an empty truck (a truck returning to the warehouse after delivering the entire payload), respectively.

---

[15] A linear fitting function was used since the force opposing the movement of the tractor is proportional to the acceleration (and trailer weight).

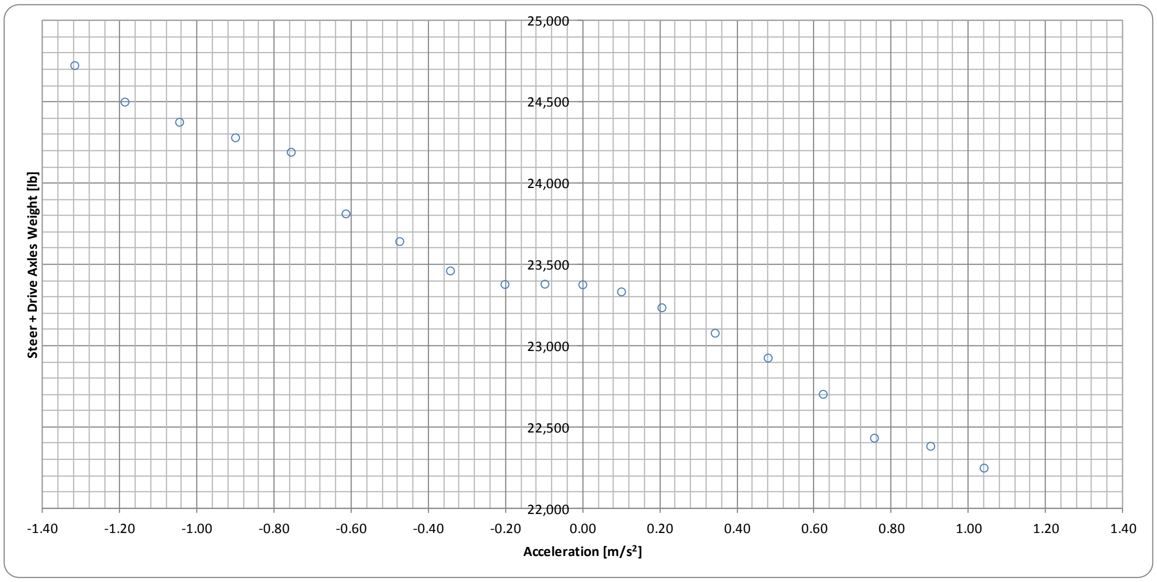


Figure 44. Tractor weight vs. acceleration—loaded truck.

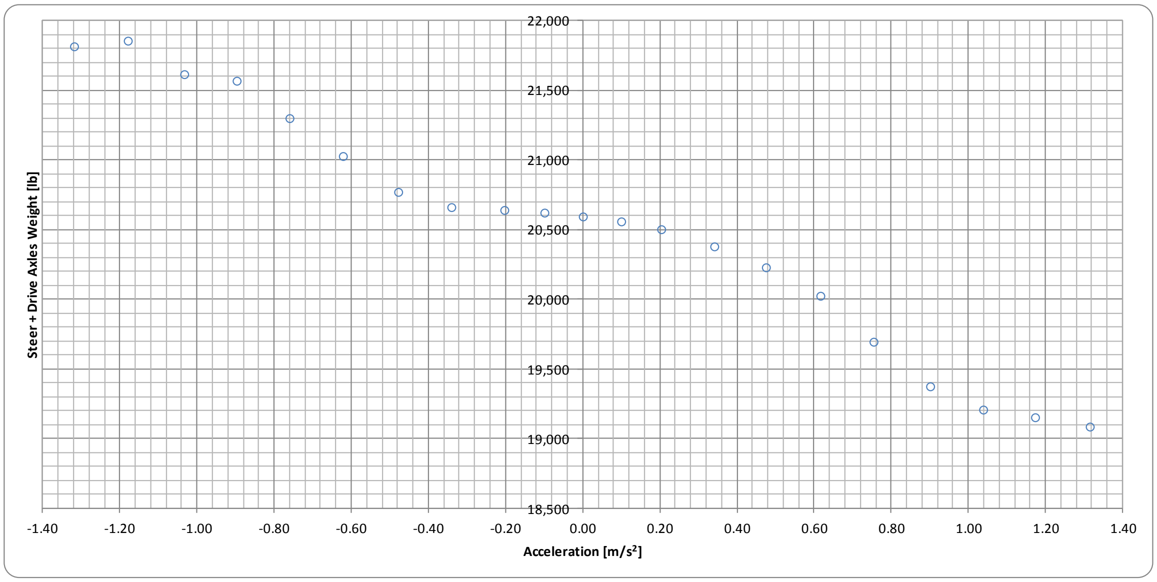


Figure 45. Tractor weight vs. acceleration—empty truck.

Notice that in both cases, the shape of the tractor weight vs. acceleration relationship follows the same pattern, with three distinct regions. Region 1 (acceleration range −1.4 to −0.2 m/s2): a close-to-linear region for the vehicle decelerating (braking), in which the Air-Weigh device registers less weight as the vehicle acceleration increases (i.e., the deceleration becomes smaller in absolute value). Region 2 (acceleration range −0.2 to 0.2 m/s2): an almost “flat” region (note: when the vehicle acceleration is very low in absolute value, then there is no “shifting” in weight among the vehicle axles and therefore the weight-acceleration relationship is constant). Region 3 (acceleration range 0.2 to 1.4 m/s2): another close-to-linear region for the vehicle accelerating in which the Air-Weigh device registers less weight as the vehicle acceleration increases.

In both cases (i.e., loaded and empty trucks) Regions 1 and 3 are very similar. Therefore, and in order to be consistent with the HTDC weight prediction models, the acceleration region (region 3) was used to develop the total-truck weight prediction model (see Capps et al., 2008, ORNL/TM-2008/122). Figure 46 and Figure 47 show the linear regression lines as well as the parameters of these lines, and the R2 (or "goodness of fit" parameter) for region 3 of the two payload cases. The high R2 indicates that, as was expected, the observed weight of the tractor decreases in a way that is very close to a linear function as the vehicle acceleration increases. Notice also that, as expected, the intercept of the linear model (i.e., weight of tractor when the vehicle is stationary) is lower for the empty-truck case than for the loaded one.

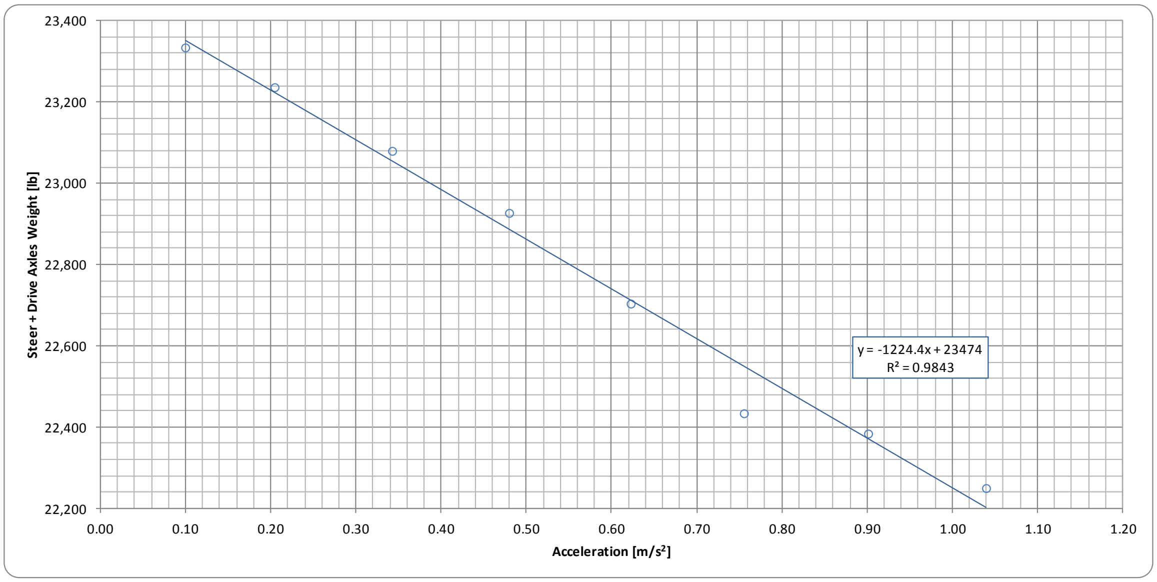


Figure 46. Linear model for tractor weight vs. acceleration—loaded truck.

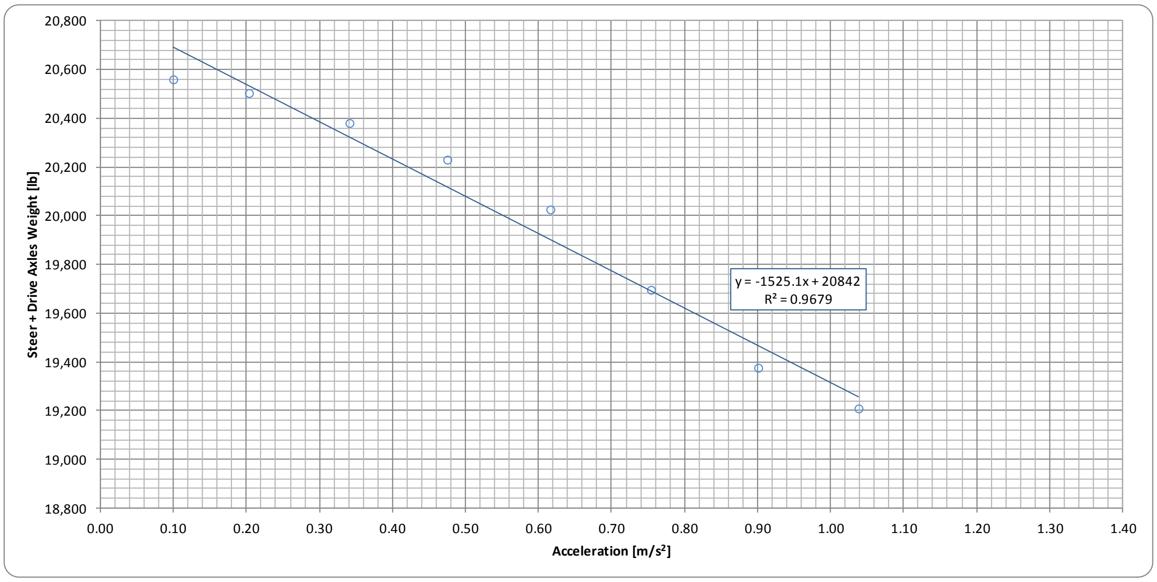


Figure 47. Linear model for tractor weight vs. acceleration—empty truck.

To develop a truck weight prediction model, the information (i.e., vehicle speed and tractor weight obtained from the onboard Air-Weigh device) collected from trips in which the vehicle total weight was obtained from CMV scales was used to generate the linear regression parameters of the tractor weight *tw* (i.e., its slope *m* and intercept *b*) as a function of vehicle acceleration *va* (call this linear regression model M1). At the same time, the total truck weight *ttw* was noted; this parameter was obtained from exogenous sources (CMV scales). All of these three parameters (*m*, *b*, and *ttw*) were determined using information from several trips in which the drivers of the vehicles stopped at an inspection station in Knox County, Tennessee at the beginning of their shift (loaded truck) and at the end of the working day (empty truck). The vehicle speed and Air-Weigh information collected from the onboard sensors while each truck traveled from the warehouse to the inspection station and from there to the first stop (i.e., two trips in which the vehicle total weight was constant, except for the fuel consumed) was used to determine parameters *m* and *b* for a loaded vehicle. The other parameter, *ttw*, was obtained from the weight ticket issued by the THP at the inspection station. Similarly, on certain days the drivers stopped at the Knox County inspection station at the end of the working day. Information collected during the trips from the last delivery stop on that day to the inspection station and from the latter to the warehouse was used to determine parameters *m* and *b* for an empty vehicle. The other parameter, *ttw*, was obtained from the weight ticket issued at the inspection station.

A second linear regression model (M2) was developed using the observed *m*’s and *b*’s, as independent variables and the *ttw*’s as the dependent variable. M2 models were developed for each of the three tractors. The external information collected at the Knox County inspection station to develop these M2 models (i.e., steer and drive axle weights, trailer axle weight, and total vehicle weight *ttw*) is presented in Table 8 and Table 9 for the loaded and empty vehicle cases, respectively.

Table 8. Weight ticket information—loaded truck

Date	Time	Vehicle ID	Axle weight [lb]			
			Steer	Drive	Trailer	Total
9/28/2009	06:04	1	9,460	14,400	9,960	33,820
9/28/2009	06:01	3	9,360	13,080	9,820	32,260
9/30/2009	06:00	1	9,700	14,460	9,620	33,780
9/30/2009	05:52	2	9,560	14,720	10,200	34,480
9/30/2009	06:33	3	9,040	13,800	9,500	32,340
10/5/2009	06:02	1	9,460	15,740	11,860	37,060
10/5/2009	05:11	2	9,460	14,000	10,200	33,660
10/5/2009	06:40	3	9,340	13,440	8,820	31,600
3/15/2010	08:56	1	9,940	14,660	9,520	34,120
3/15/2010	05:12	2	9,080	14,400	11,960	35,440
3/15/2010	05:55	3	9,100	13,100	8,540	30,740
3/16/2010	07:47	1	9,860	15,020	13,240	38,120
3/16/2010	07:14	2	9,060	13,620	11,160	33,840
3/16/2010	04:28	3	9,280	13,720	11,260	34,260
3/18/2010	05:09	1	9,720	14,560	11,720	36,000
3/18/2010	04:06	2	9,260	14,600	10,540	34,400
3/18/2010	06:10	3	9,180	13,400	9,540	32,120
9/28/2009	06:04	1	9,460	14,400	9,960	33,820

Table 9. Weight ticket information—empty truck

Date	Time	Vehicle ID	Axle weight [lb]			
			Steer	Drive	Trailer	Total
10/15/2009	16:18	1	9,620	11,820	7,480	28,920
10/15/2009	16:39	2	9,080	10,960	6,960	27,000
10/15/2009	14:11	3	9,020	10,920	6,740	26,680
10/16/2009	14:43	1	9,480	11,820	7,260	28,560
10/16/2009	12:42	2	9,020	11,200	7,380	27,600
10/16/2009	15:03	3	9,240	11,000	6,860	27,100
3/15/2010	13:15	2	8,860	11,140	6,920	26,920
3/15/2010	14:09	3	8,880	10,840	6,740	26,460
3/16/2010	16:27	1	9,480	11,740	7,400	28,620
3/16/2010	15:36	2	8,900	10,760	6,820	26,480
3/16/2010	13:29	3	9,520	11,000	6,960	27,480
3/18/2010	15:01	1	9,380	11,600	7,480	28,460
3/18/2010	14:02	2	9,000	11,020	6,860	26,880
3/18/2010	13:47	3	9,140	10,860	6,880	26,880

The methodology to determine truck total weight was as follows. Using the tractor Air-Weigh readings, parameters m, b, and tw (i.e., model M1 parameters) were generated for each time segment in those trips in which the truck was moving, as explained previously. Those parameters were then used as inputs in the corresponding tractor M2 model to predict the truck total weight. The latter quantity was then assigned to the corresponding records in the database of collected information.

4.2.2 Calibration of Data Bus Fuel Readings

Because of the focus of the MTDC project on the study of FE, the available fuel-related vehicle data bus signals were studied to understand the accuracy of these signals. Before the FOT began, a short-term fuel study was performed to understand the relationship between the actual fuel usage and similar data available from the vehicle's data bus. Drivers of four combination vehicles from the partnering fleet kept a fuel log for the tractor units for one month.[16] Records from the vehicles' electronic onboard recorders (EOBRs) provided similar information based on signals from the J1708 vehicle data bus. Of the 20 segments for which manual and automatically recorded (J1708-based) logs were available, there was one outlier with a value of more than four standard deviations below the mean. This outlier was the result of erroneous data recording and therefore was eliminated from the dataset. The remaining data is shown in Figure 48.

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[16] The refrigerated trailer units are fueled separately, and the amount of this fuel is not included in the analysis.

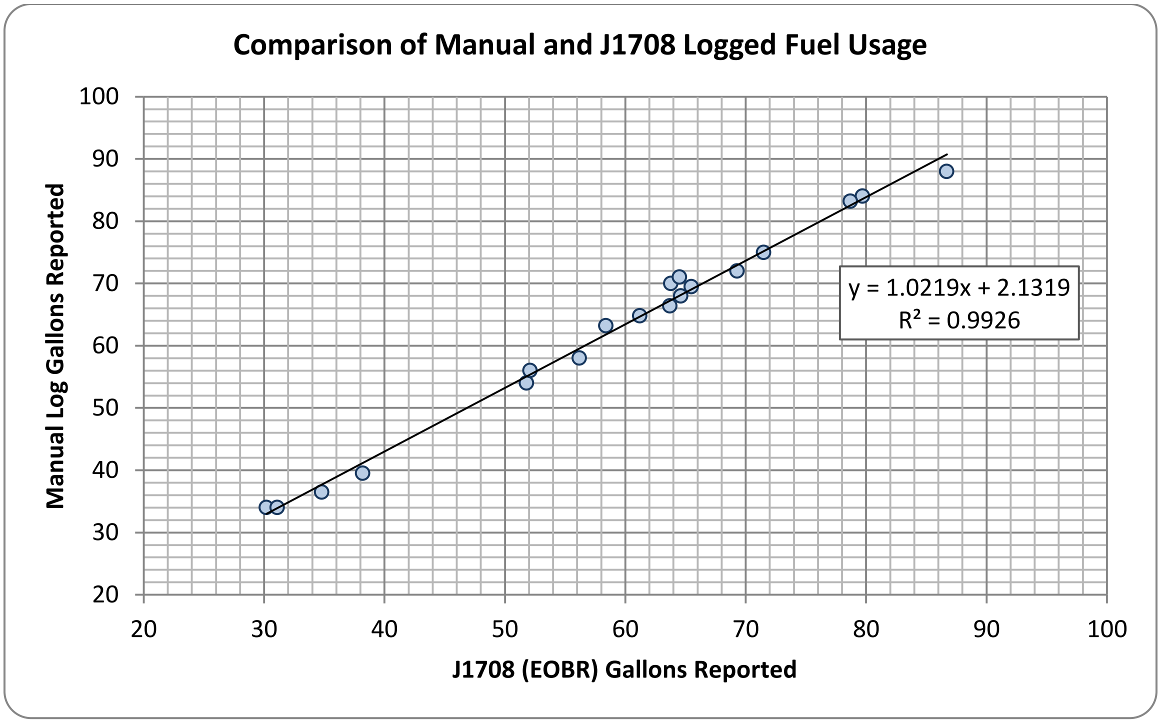

Figure 48. Gallons of fuel used—manual log values vs. EOBR-reported values for all participating vehicles.

This plot indicates that the reported gallons of fuel used from the vehicle's J1708 data bus provides an accurate representation of the actual fuel used. However, the DAS used in the FOT recorded this value from the newer J1939 data bus rather than the older J1708 data bus. EOBR logs were obtained for a month of recorded duty cycle data to compare these two data buses. As shown in Figure 49, the two data sets were virtually identical, indicating that the J1939 provides a basis for accurate fuel usage calculations.

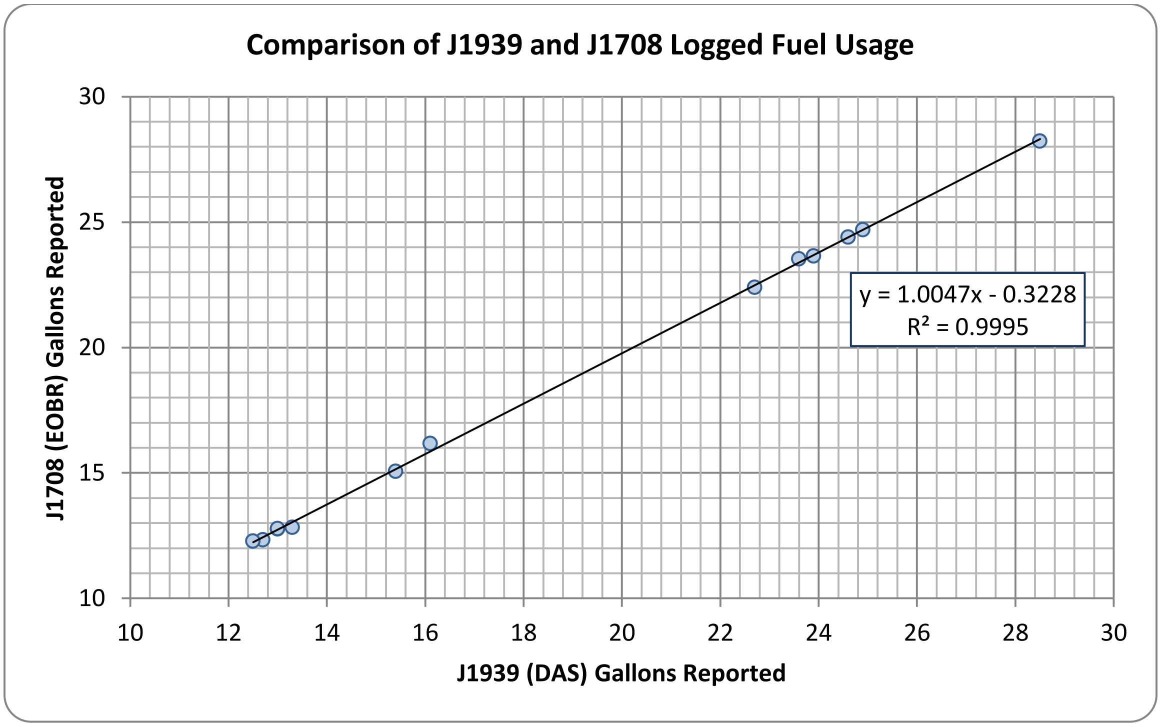

Figure 49. Gallons of fuel used—EOBR-reported values vs. DAS-recorded values.

4.3 GENERAL STATISTICS

The main focus of the data analysis was on the FE of Class-7 vehicles operating in different vocations and under different payload conditions. The analysis presents some general statistics that summarize the operations of the two vocations (i.e., combination trucks and transit buses) that participated in the first phase of the MTDC project. An analysis of the FE of these vehicles follows, with the payload dimension added later in this chapter. To add to this dimension, a vehicle total weight model was developed for the combination trucks as discussed earlier and was used to assign total vehicle weight to each record in the database. An investigation of the variability of duty cycles (both on freeways and on surface street) is also presented in this section.

4.3.1 General Operations Statistics

During the 1 year data collection period, the six participating vehicles logged over 105,000 miles (45,400 for the combination trucks and 59,400 for the transit buses) and consumed over 17,000 gal of fuel (6,000 for the combination trucks and 11,300 for the transit buses) while conducting business in the East Tennessee area. Figure 50 to Figure 52 show the area of operation of the three combination trucks, and Figure 53 to Figure 55 present the superimposed routes for the three transit buses during the 1-year data collection period.

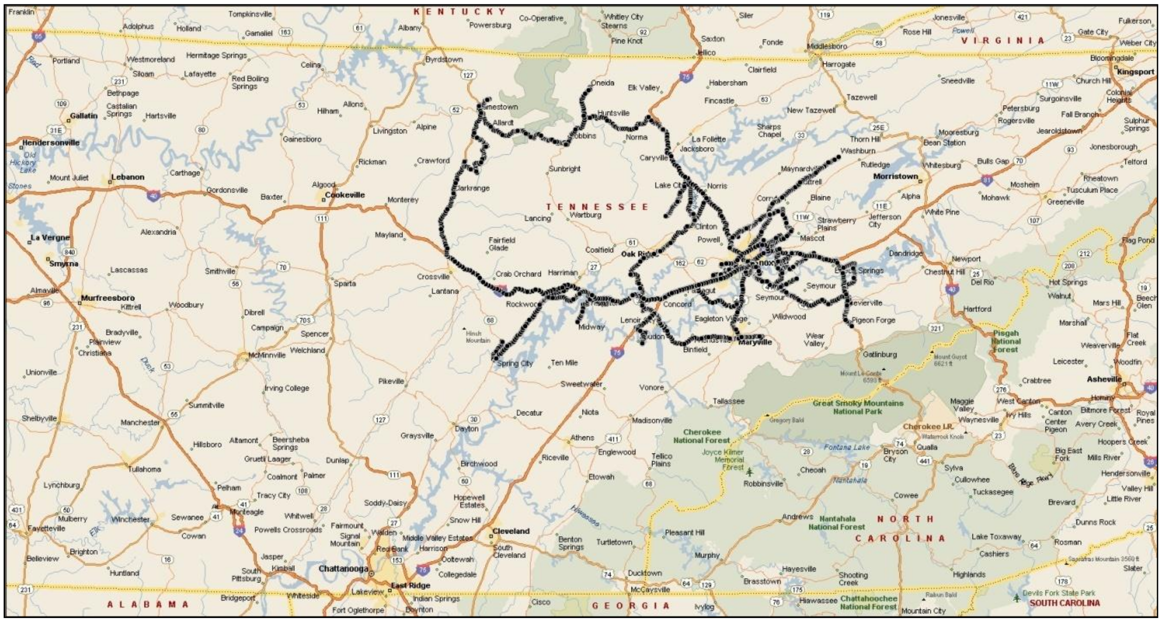

Figure 50. Combination truck 1 (MTDC vehicle 1) coverage area.

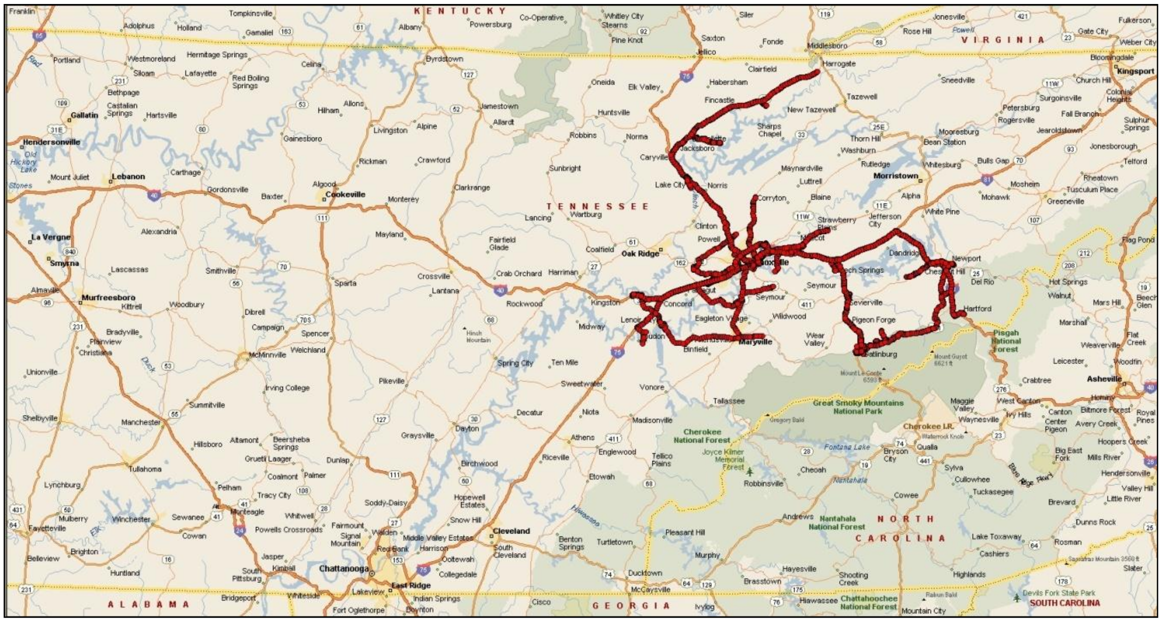

Figure 51. Combination truck 2 (MTDC vehicle 2) coverage area.

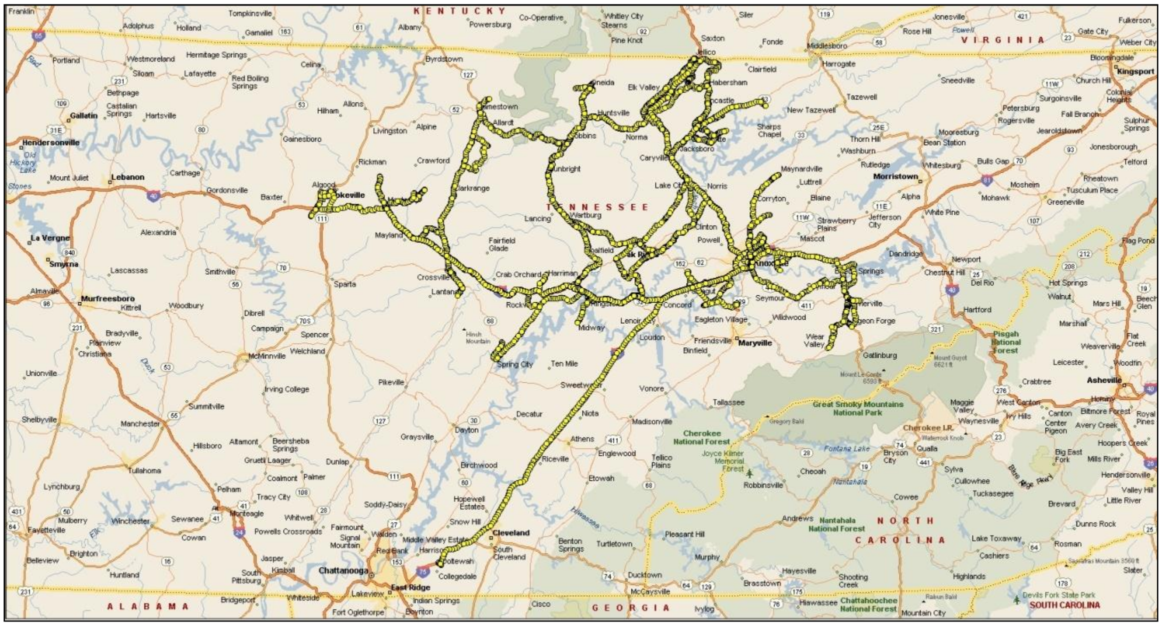

Figure 52. Combination truck 3 (MTDC vehicle 3) coverage area.

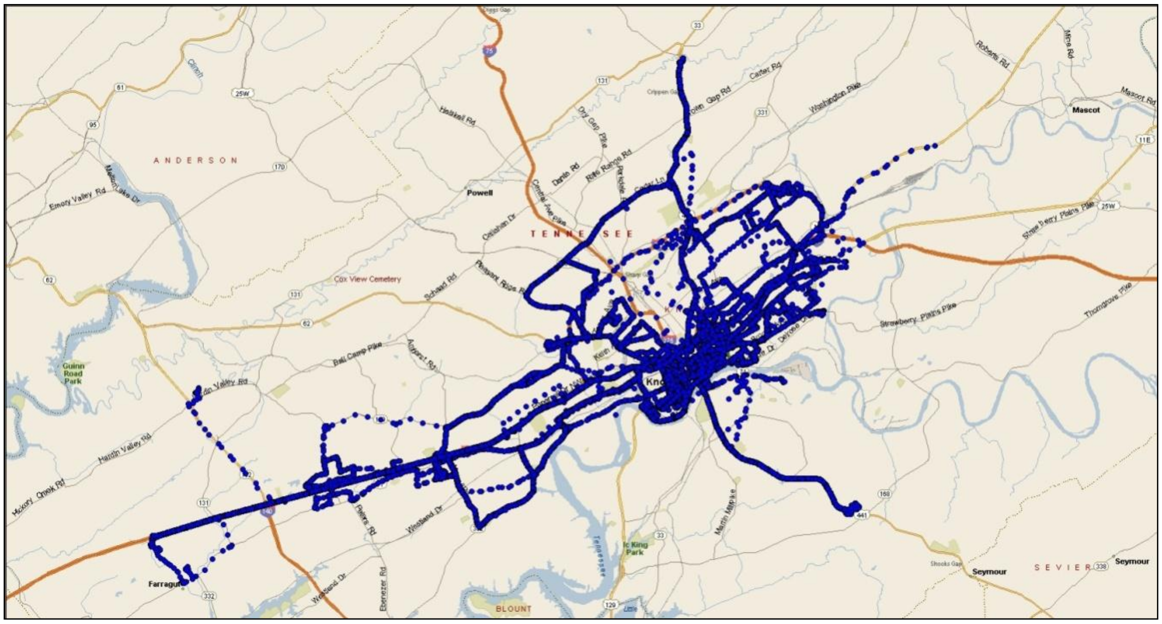

Figure 53. Transit bus 1 (MTDC vehicle 4) coverage area.

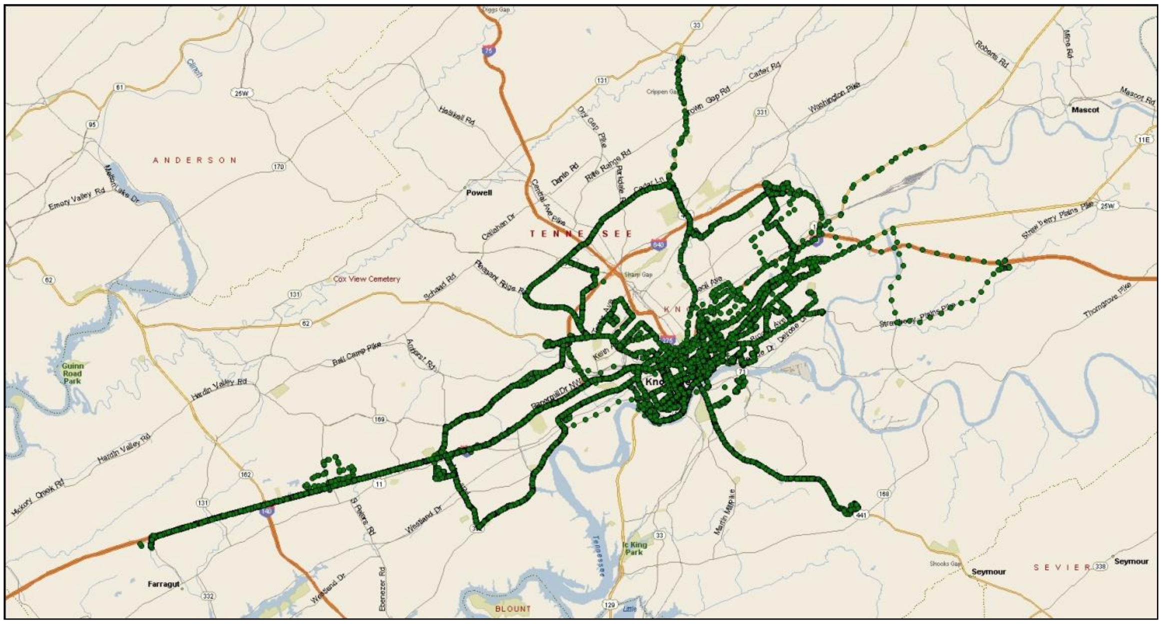

Figure 54. Transit bus 2 (MTDC vehicle 5) coverage area.

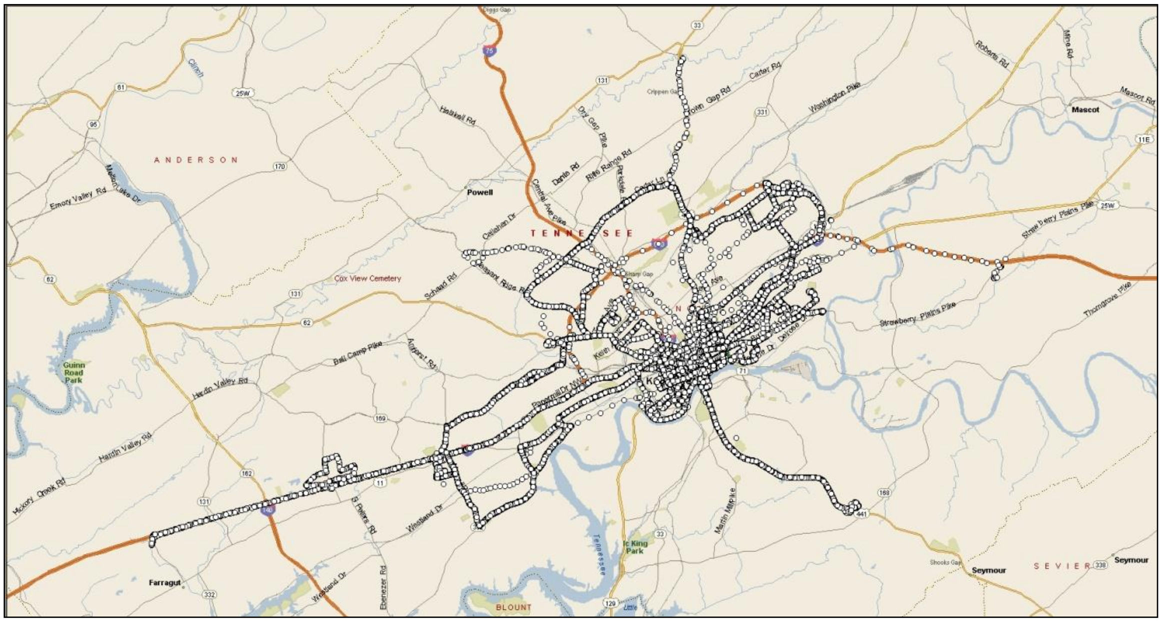

Figure 55. Transit bus 3 (MTDC vehicle 6) coverage area.

Table 10 and Table 11 present a summary of these statistics for each one of the three participating combination trucks and the three transit buses, respectively. The tables also include information regarding FEs for the entire data collection period, for each of the six vehicles, as well as their overall FE. These calculations were made using fuel consumption information obtained from the vehicles' data bus (last row in Table 10 and Table 11) and include both the fuel consumed while the vehicle is moving and the fuel spent while idling.

Table 10. General statistics for the combination trucks

	MTDC vehicle			Grand total
	1	2	3	
Distance traveled* [miles]	18,483	6,547	20,390	45,419
Total time [h]	562	191	556	1,309
Average speed [mph]	32.9	34.3	36.7	34.7
Average moving speed [mph]	42.4	42.8	43.8	43.0
Total fuel [gal]	2,568	841	2,597	6,006
Overall fuel efficiency** [mpg]	7.197	7.783	7.851	7.562

*Computed with vehicle databus information (integration of vehicle speed over time).
**Computed with vehicle databus information on fuel consumption, and integration of vehicle speed over time.

Table 11. General statistics for the transit buses

	MTDC vehicle			Grand total
	4	5	6	
Distance traveled* [miles]	27,347	9,215	22,867	59,429
Total time [h]	2,482	854	1,909	5,245
Average speed [mph]	11.0	10.8	12.0	11.3
Average moving speed [mph]	24.1	24.9	25.1	24.6
Total fuel [gal]	5,432	1,764	4,179	11,374
Overall fuel efficiency** [mpg]	5.035	5.224	5.472	5.225

*Computed with vehicle databus information (integration of vehicle speed over time).
**Computed with vehicle databus information on fuel consumption, and integration of vehicle speed over time.

The information collected was used to generate distributions of idling time and idling fuel consumed as a percentage of total time and total fuel consumed, respectively. Seven intervals of time were considered, ranging from 0–5 min (i.e., the vehicle was idling—vehicle static and engine running—for less than 5 min) to more than 240 min (4 h). The short intervals corresponded to idling due to traffic conditions (i.e., delays at traffic lights, congestion, and bus dwell time at bus stops while loading and unloading passengers) and the largest one with overnight parking and garage idling. The idling information is presented in Table 12 and Table 13 for the combination trucks and the transit buses, respectively.

For the combination trucks (Table 12), the largest proportion of idling time (63%) and fuel consumed while idling (59%) correspond to idling intervals of 0–5 min (i.e., traffic congestion and delay at traffic signals). This is followed by intervals of 5–15 min of idling time (25% of idling time and 28% of fuel consumption while idling), and 15–60 min. The latter is mostly idling while stopping for a delivery. The 120–180 min interval is due to vehicle maintenance or repair at the company garage (9.6 h over a period of 1 year for the three vehicles combined).

The transit buses also spent most of their idling time (35%) in congestion and bus dwell times (0–5 min idling interval), which also consumed the largest proportion of fuel spent while idling (see Table 13). However, as opposed to the combination trucks, the transit buses spent 22% of their idling time in intervals longer than 4 h, consuming about 21% of the fuel while idling during these long periods. These long idling times were observed mostly at the parking lot while the vehicles were waiting to start a trip.

Table 12. Distributions of time spent and fuel consumed while idling (combination trucks)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	157.2	63.7	12.0	71.1	59.4	1.2
5–15	61.5	24.9	4.7	33.5	28.0	0.6
15–60	15.1	6.1	1.2	10.6	8.9	0.2
60–120	3.3	1.3	0.2	1.4	1.2	0.0
120–180	9.6	3.9	0.7	3.0	2.5	0.1
180–240	0.0	0.0	0.0	0.0	0.0	0.0
240+	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**247**	**100**	**18.8**	**120**	**100**	**2.0**

Table 13. Distributions of time spent and fuel consumed while idling (transit buses)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	963.1	34.5	18.4	939.7	34.8	8.3
5–15	332.9	11.9	6.3	324.9	12.0	2.9
15–60	304.0	10.9	5.8	306.2	11.3	2.7
60–120	288.7	10.3	5.5	267.6	9.9	2.4
120–180	169.4	6.1	3.2	174.7	6.5	1.5
180–240	117.6	4.2	2.2	113.9	4.2	1.0
240+	615.5	22.0	11.7	575.9	21.3	5.1
TOTAL	**2,791**	**100**	**53.2**	**2,703**	**100**	**23.8**

4.3.2 Class-7 Vehicle Fuel Efficiency

Using the information collected in the project, it is possible to compute the FEs of combination trucks and transit buses. The overall FEs, that is the FEs computed taking into consideration idling times, as well as the moving FEs (i.e., fuel consumed only when the vehicle was moving) are presented in Table 14 and Table 15 for the three combination trucks and three transit buses, respectively. The tables also present the percentage difference between overall and moving FEs for each vehicle. Notice that for the transit buses, the percentage difference between overall and moving FEs is much higher (between 10 and 20 times higher) than for the combination trucks. Some of this difference can be attributed to differences among different types of vehicles (e.g., transmission type, age), but most is due to idling differences. Although the total miles traveled by the two sets of vehicles during the year-long project is slightly higher (about 33% larger) for the transit buses than for the combination trucks, the former consumed almost 22 times (or 2150%) more fuel than the latter while idling (see Table 10 to Table 13). Using the moving FEs information, it is possible to see that the FEs are different, almost 13% higher for the combination trucks than for the transit buses.

Table 14. Overall and moving fuel efficiency—combination trucks

MTDC vehicle	Overall FE [mpg]	Moving FE [mpg]	Percent difference
1	7.197	7.407	2.91
2	7.783	7.939	2.01
3	7.851	7.992	1.80
All vehicles	**7.562**	**7.736**	**2.30**

Table 15. Overall and moving fuel efficiency—transit buses

MTDC vehicle	Overall FE [mpg]	Moving FE [mpg]	Percent difference
4	5.035	6.580	30.70
5	5.224	7.002	34.03
6	5.472	7.150	30.66
All vehicles	**5.225**	**6.854**	**31.19**

4.4 WEIGHT ESTIMATION

4.4.1 Weight Estimation Model

The weight prediction models described in Section 3.2.1 were applied to all of the information collected during the project by the combination trucks. Figure 56 to Figure 58 present the distributions of measured steer and drive axle weights and modeled truck weight for vehicles 1 to 3, respectively. Those distributions were built by counting trips (i.e., from a particular stop to the next stop, with stopping times larger than 10 min) that presented the same payload level, and using 1,000 lb payload bins. Notice that there were a few trips on which the weight of the tractor was about 14,000 lb; those were trips within the warehouse parking area on which the tractor did not have any trailer attached. Notice also that the three combination trucks had different total vehicle weight distributions. This is mostly due to the fact that each of the three vehicles, in general, repeated the same delivery routes week after week, and to the length of the routes (i.e., longer routes visited more convenience and other stores than shorter routes, and the vehicles were heavier on the longer routes). For example, Combination Truck 3 carried, on average, heavier payloads (see Table 16) since it traveled farther from the warehouse than the other two vehicles (see Figure 56 to Figure 58), visiting each delivery stop with less frequency.

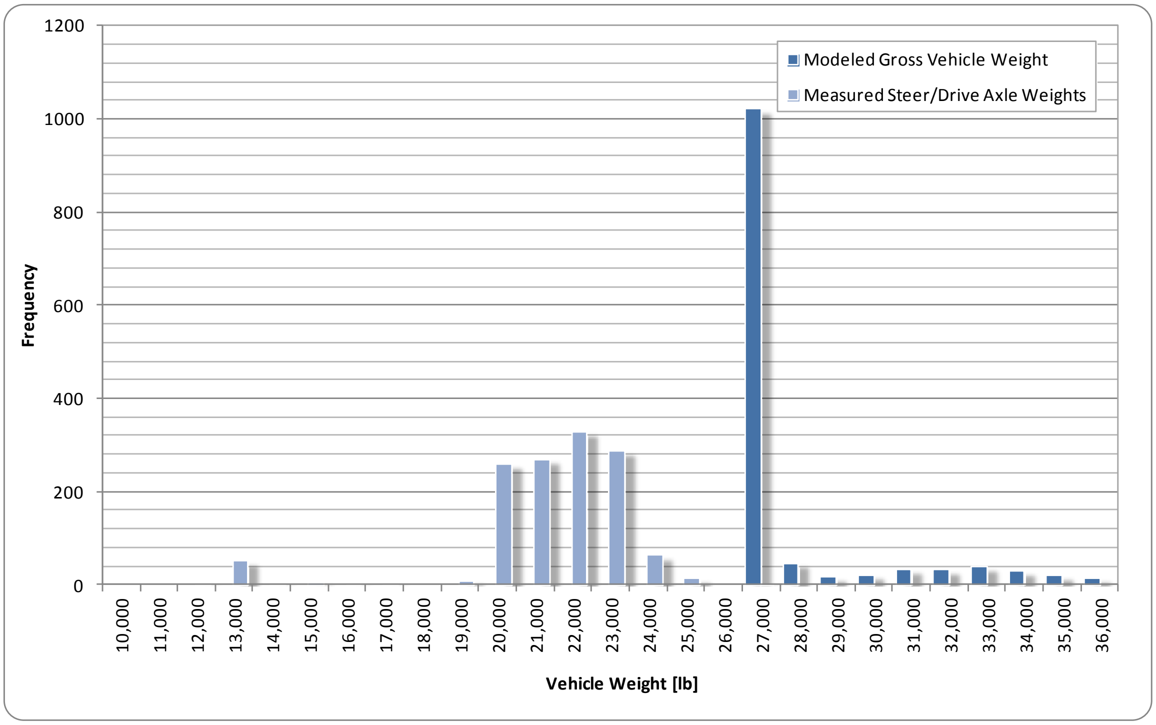

Figure 56. Combination truck 1 (MTDC vehicle 1) frequency distributions of measured steer/drive axle weights and modeled GVW.

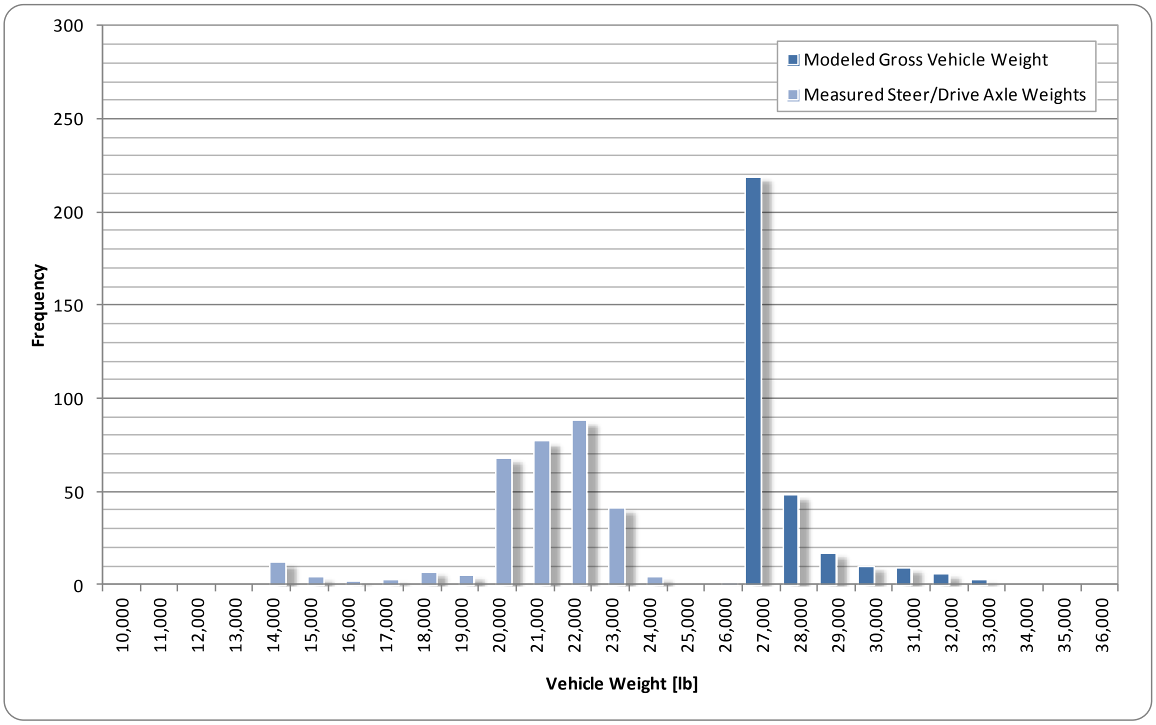

Figure 57. Combination truck 2 (MTDC vehicle 2) frequency distributions of measured steer/drive axle weights and modeled GVW.

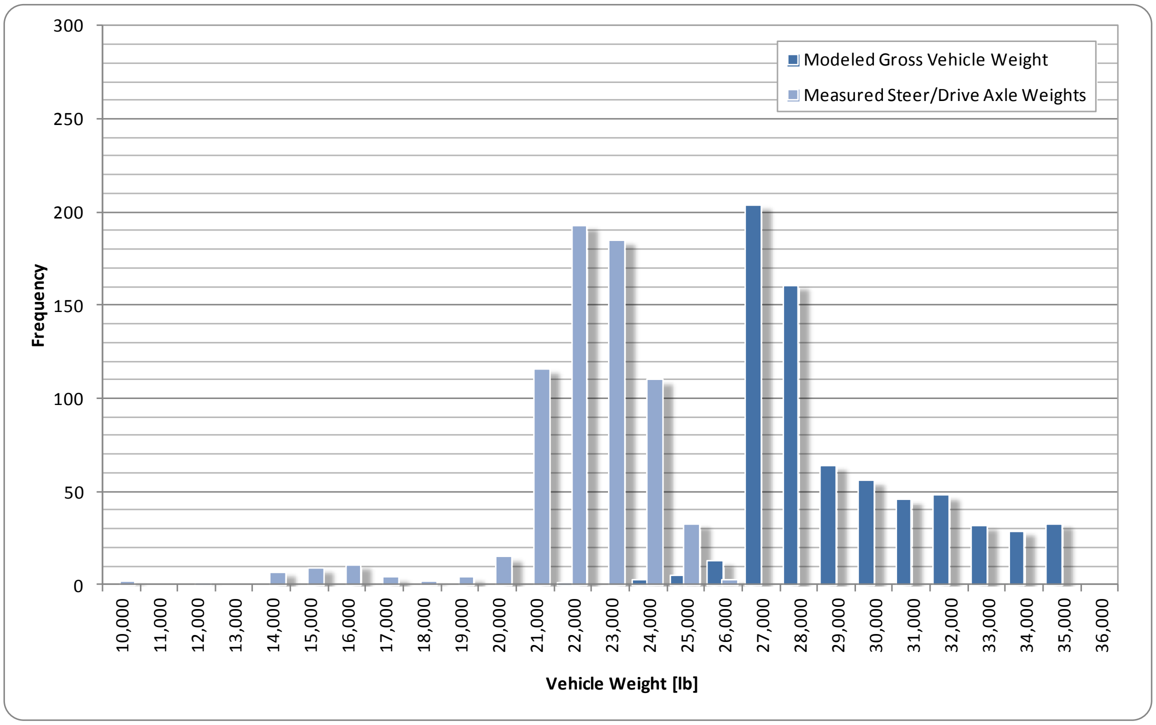

Figure 58. Combination truck 3 (MTDC vehicle 3) frequency distributions of measured steer/drive axle weights and modeled GVW.

In the case of the transit buses, it was not necessary to develop a weight prediction model since the vehicles were equipped with the Air-Weigh device that measured total vehicle weight continuously. Total vehicle weight distributions were built in a similar manner to those of the combination trucks discussed earlier. These distributions are presented in Figure 59 to Figure 61. Transit Buses 1 and 2 had similar, and skewed, total vehicle weight distributions with a higher frequency of trips with heavier payloads (i.e., more passengers) than the mode of the distribution (i.e., the value that occurs most frequently in the distribution). In contrast, Transit Bus 3 showed a more normally distributed (i.e., less skewed) total vehicle weight with a similar number of trips with lighter and heavier payloads. This is the result of the different routes that these vehicles followed during the year-long data collection effort.

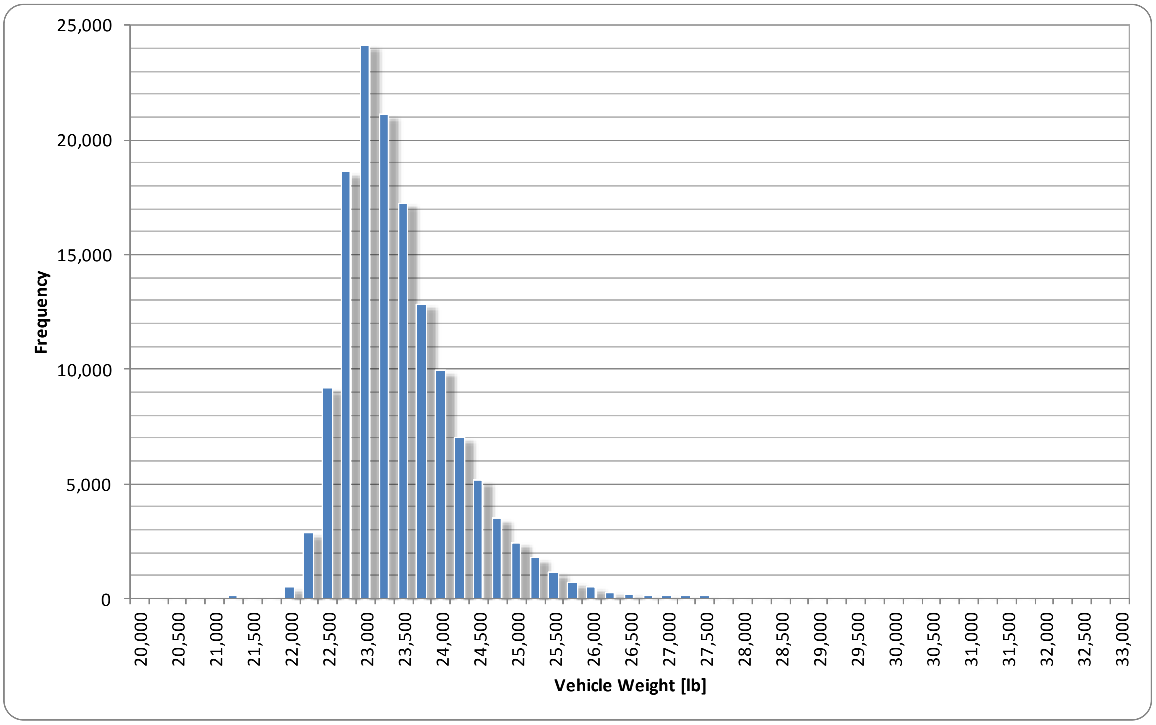

Figure 59. Transit bus 1 (MTDC vehicle 4) frequency distribution of GVW.

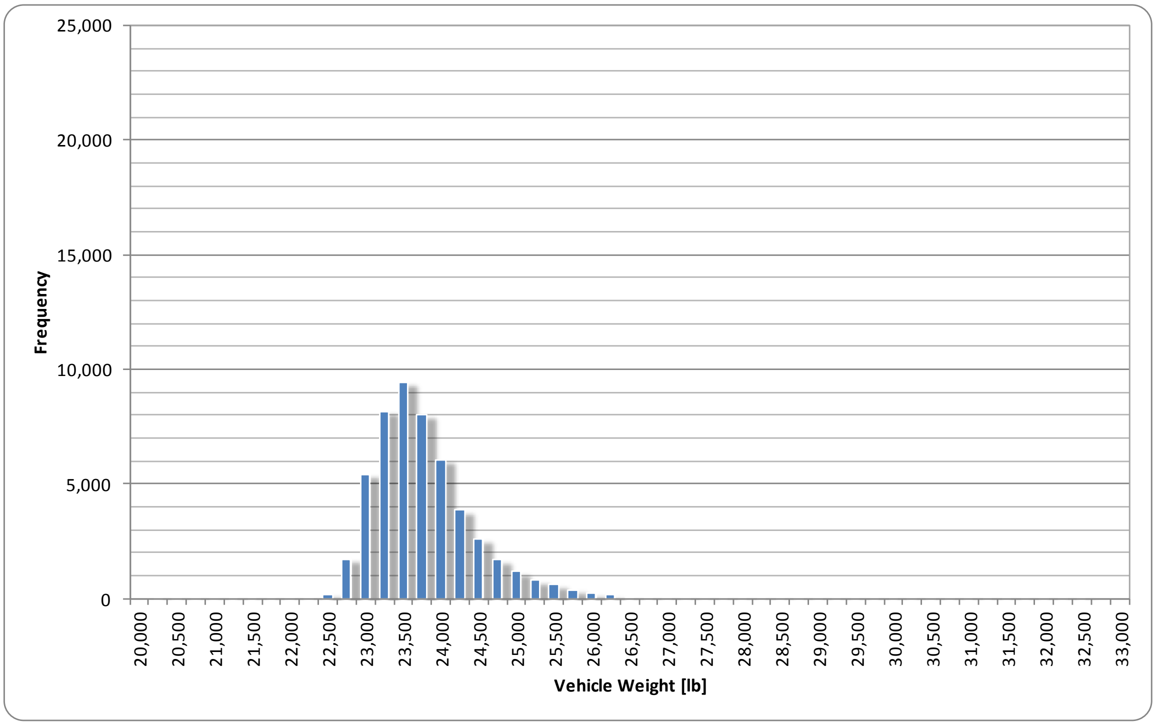

Figure 60. Transit bus 2 (MTDC vehicle 5) frequency distribution of GVW.

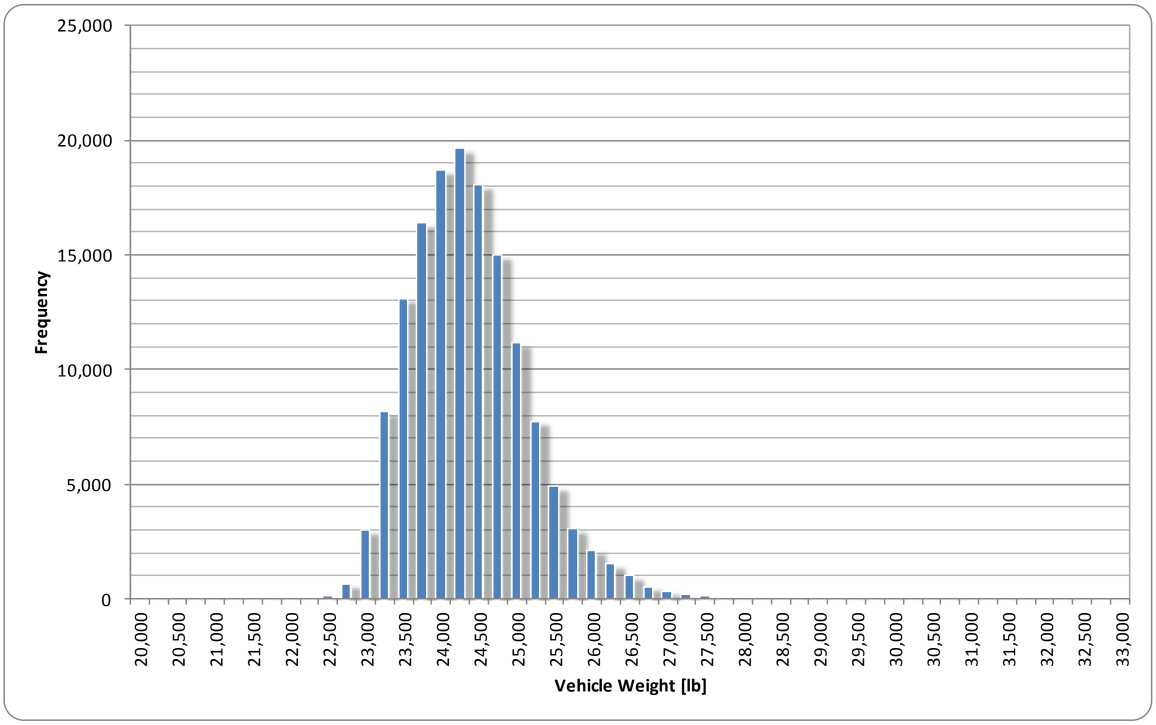

Figure 61. Transit bus 3 (MTDC vehicle 6) frequency distribution of GVW.

4.4.2 Effect of Vehicle Weight on Fuel Efficiency

One important variable affecting the FE of any vehicle is its weight or payload. The previous subsections showed FE measurements that were obtained without controlling for any particular variable since it could be assumed that any of the participating vehicles would experience the same situations (terrain, weather, payload, etc.) over the course of the year-long experiment. In this subsection the weight of the vehicle is introduced as a controlling variable to study how the payload affects the FE of combination trucks and transit buses.

To do this, the search engine developed by ORNL was used to parse the data by vehicle load level. For the combination trucks, the vehicle weight was divided into four categories: (1) Tractor and Empty Trailer (this category also includes tractor-only trips), (2) Light Load (total vehicle weight between 23,000 and 26,999 lb); (3) Medium Load (total vehicle weight between 27,000 and 31,999 lb); and (4) Heavy Load (total vehicle weight above 32,000 lb). In the case of the transit buses, the vehicle weight was divided into three categories: (1) Empty Bus (vehicle weight less than 22,500 lb), 2) Light Fare (total vehicle weight between 22,500 and 25,499 lb), and (3) Heavy Fare (total vehicle weight above 25,500 lb).

Table 16 and Table 17 present summary statistics of the distribution of payloads grouped under the weight levels for the combination trucks and transit buses, respectively. The tables show the average weight in each load level category as well as the percentage of the time that the vehicle carried a load that was within that category. On average, the combination trucks weighed between 27,700 and 29,000 lb and the buses weighed between 23,000 and 23,800 lb. Very few trips in the “tractor and empty trailer” category were observed (these were mostly trips within the warehouse area). Most of the trips for vehicle 2 (98%) were at a light or medium load; for vehicle 3, almost 70% of the trips were at medium and high loads, as explained previously.

Table 16. Combination truck weight-level statistics

MTDC vehicle	Load level									
	Any payload		Tractor and empty trailer		Light load		Medium load		Heavy load	
	Percent of time	Average weight [lb]	Percent of time	Average weight [lb]	Percent of time	Average weight [lb]	Percent of time	Average weight [lb]	Percent of time	Average weight [lb]
1	100.0	28,166	0.0*	0	70.2	26,557	15.5	29,691	14.3	34,398
2	100.0	27,713	0.0*	0	58.7	26,838	40.6	28,894	0.7	32,460
3	100.0	29,038	0.4	22,785	32.4	26,313	48.0	29,132	19.2	33,528

*Negligible

Table 17. Transit bus weight-level statistics

MTDC vehicle	Load level							
	Any fare		Empty		Light fare		Heavy fare	
	Percent of time	Average weight [lb]	Percent of time	Average weight [lb]	Percent of time	Average weight [lb]	Percent of time	Average weight [lb]
4	100.0	22,958	28.1	22,198	69.9	23,176	2.0	26,027
5	100.0	23,230	7.6	22,257	89.7	23,222	2.7	26,296
6	100.0	23,854	3.2	22,274	88.7	23,734	8.1	25,775

Transit buses 2 and 3 (MTDC vehicles 5 and 6) operated almost 90% of the time with a light fare as defined above. Vehicle 6 also had the largest average weight, indicating that this was the vehicle that carried the largest number of passengers (on average). Transit bus 1 (MTDC vehicle 4), on the other hand spent almost 30% of the time at an empty level. This was mostly due to idling at the parking garage. This vehicle had the lowest overall FE of the three buses (see Table 15).

To generate the distribution of FE under the payload levels described, 10-mile segments were considered for which the FE was computed and counted as one observation. Table 18 presents the results of this analysis for the combination trucks. Under each load level category, the column labeled “Average FE” contains the average of the FEs across all the 10-mile segments, with the column immediately to the right presenting the standard deviation of the distribution. Overall, as expected, the FE decreases as the payload increases. However, because the payload categories are very narrow and low (those combination trucks never made any trips that were above 42,000 lb, far below the legal weight limit for Class-7 trucks), the variations of the FEs are not significant.

The distributions of FEs for each load-level and for all the three vehicles combined are presented in graphical form in Figure 62. For the majority of the combination truck trips, the load level was light and medium (i.e., between 23,000 and 32,000 lb).

Table 18. Fuel efficiency as a function of load level—combination trucks

MTDC vehicle	Load Level							
	Tractor with empty trailer		Light load		Medium load		Heavy load	
	Average FE [mpg]	Standard deviation [mpg]	Average FE [mpg]	Standard deviation [mpg]	Average FE [mpg]	Standard deviation [mpg]	Average FE [mpg]	Standard deviation [mpg]
1	#N/A*	#N/A*	7.520	1.020	7.191	1.021	7.091	1.065
2	#N/A*	#N/A*	8.013	1.422	7.838	1.328	6.944	1.261
3	8.299	1.708	8.345	1.715	7.667	1.470	7.904	1.452
All vehicles	**8.299**	**1.708**	**7.997**	**1.493**	**7.574**	**1.345**	**7.532**	**1.351**

*Negligible data collected.

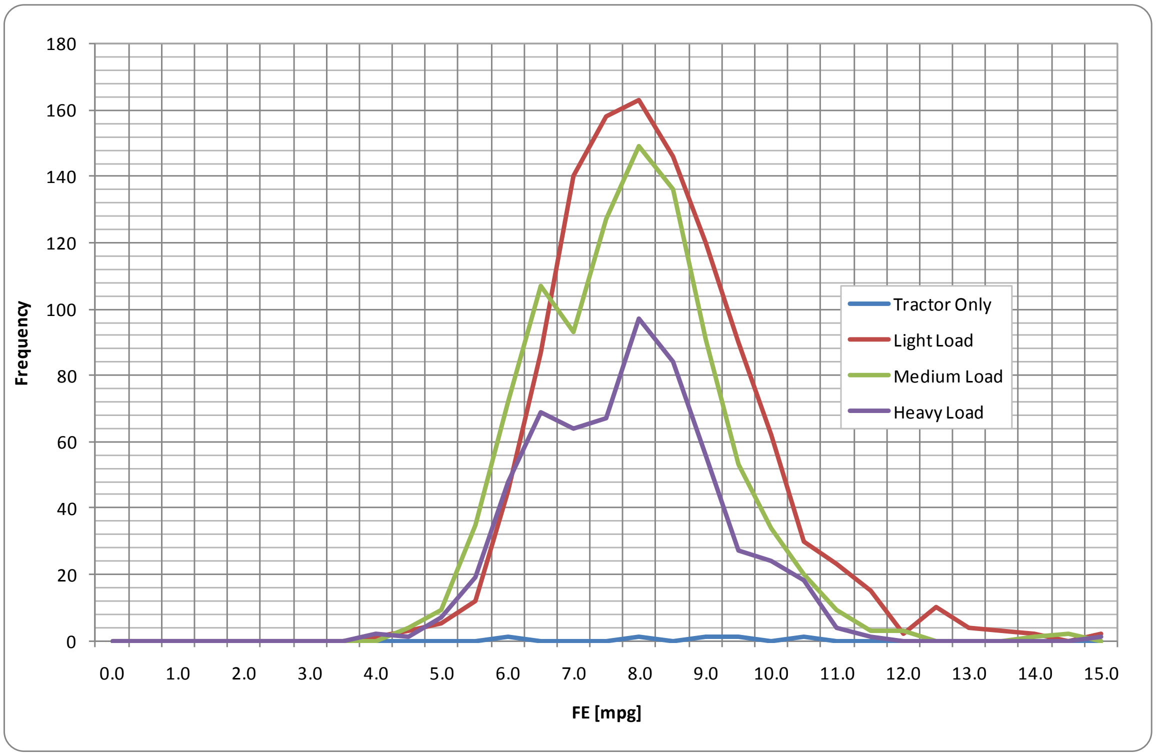

Figure 62. Fuel efficiency frequency distributions as a function of load level—combination trucks.

In the case of the transit buses (see Table 19) the relationship between FE and vehicle weight is not as would be predicted (i.e., the expectation is decreasing FE with increasing payload). This is due to several factors. First, when the vehicle is empty (lowest payload), it spends a considerable amount time idling as discussed previously. This results in very low FEs for this load-level category. At the other end of the spectrum, the highway routes (express routes) are the ones that carry the largest number of passengers. The buses on these routes spend very little dwell time (there are fewer bus stops) and encounter the fewest traffic lights. This results in FEs that are higher than regular surface-street routes (light fare) with many more stops (bus stops and traffic signals). Notice that in Table 19, vehicle 4 has a very low standard deviation for the heavy fare case. This was because there were only two observations for that case.

The distributions of FEs for each load-level and all the three transit buses combined are presented in graphical form in Figure 63. For the majority of the transit bus trips, the load level was light fare (i.e., between 22,500 and 25,500 lb).

Table 19. Fuel efficiency as a function of load level—transit buses

MTDC vehicle	Load level					
	Empty		Light fare		Heavy fare	
	Average FE [mpg]	Standard deviation [mpg]	Average FE [mpg]	Standard deviation [mpg]	Average FE mpg]	Standard deviation [mpg]
4	3.261	1.751	4.941	1.191	3.433	0.084
5	4.465	1.368	4.724	1.656	7.412	0.980
6	3.953	1.818	4.820	1.466	5.317	0.906
All vehicles	**3.397**	**1.748**	**4.866**	**1.373**	**5.685**	**1.450**

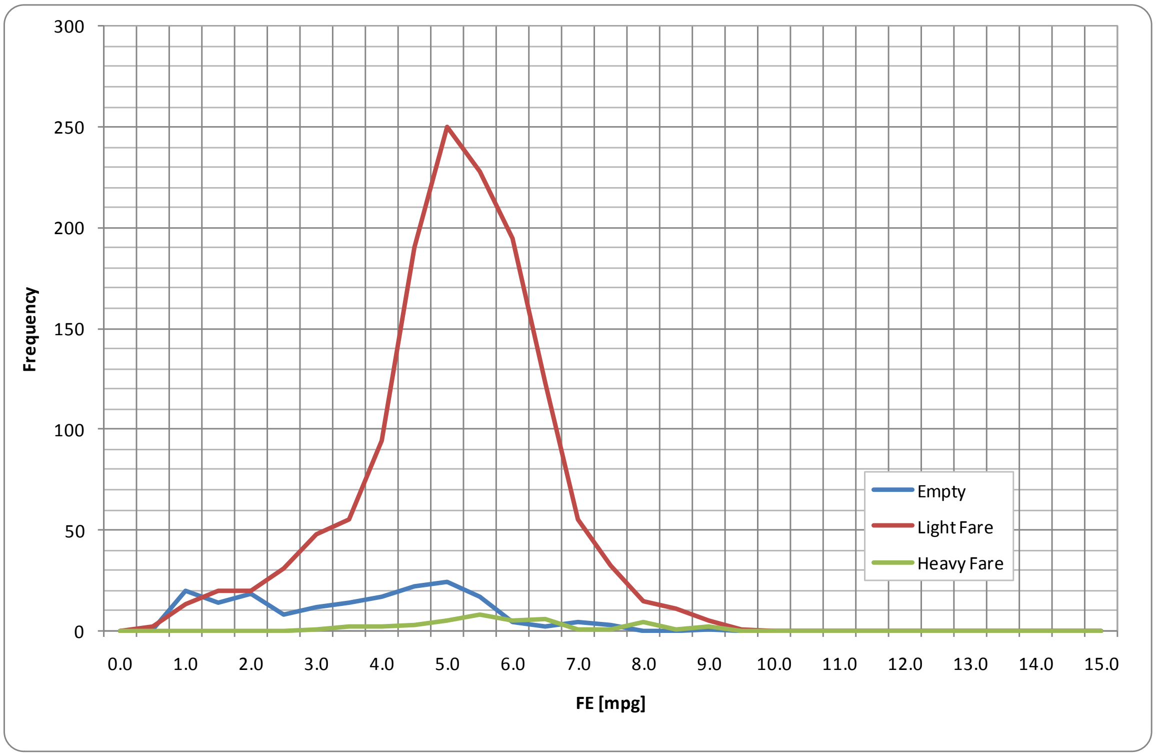

Figure 63. Fuel efficiency frequency distributions as a function of load level—transit buses.

4.5 CLASSIFICATION OF DUTY CYCLES

4.5.1 Transit Bus Highway Duty Cycles

The data collected in this project can also be used to investigate the variability that may exist in duty cycles generated by the same vocation and following the same route. To do so, two sets of duty cycles collected from the data gathered by the transit buses were identified. The first set focused on freeway duty cycles. A 19 km segment of I-40 in Knoxville, Tennessee, was selected (see Figure 64) and the corresponding duty cycles extracted from the database. This is a segment of urban highway used in several KAT bus routes in both the westbound and eastbound directions. For this study, only the westbound direction was addressed.

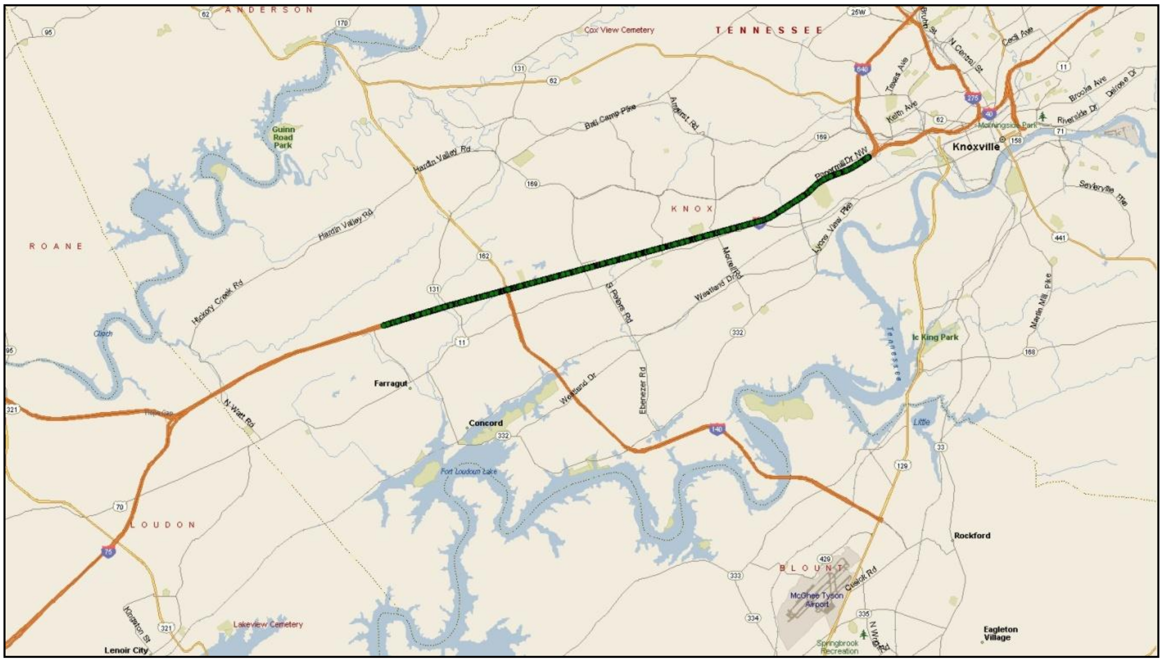

Figure 64. Transit bus highway duty cycle route.

Seventy-four highway duty cycles with the characteristics described above were selected. The majority of these duty cycles corresponded to the morning peak hour, with considerably fewer occurring during the afternoon peak hour (see Figure 65).

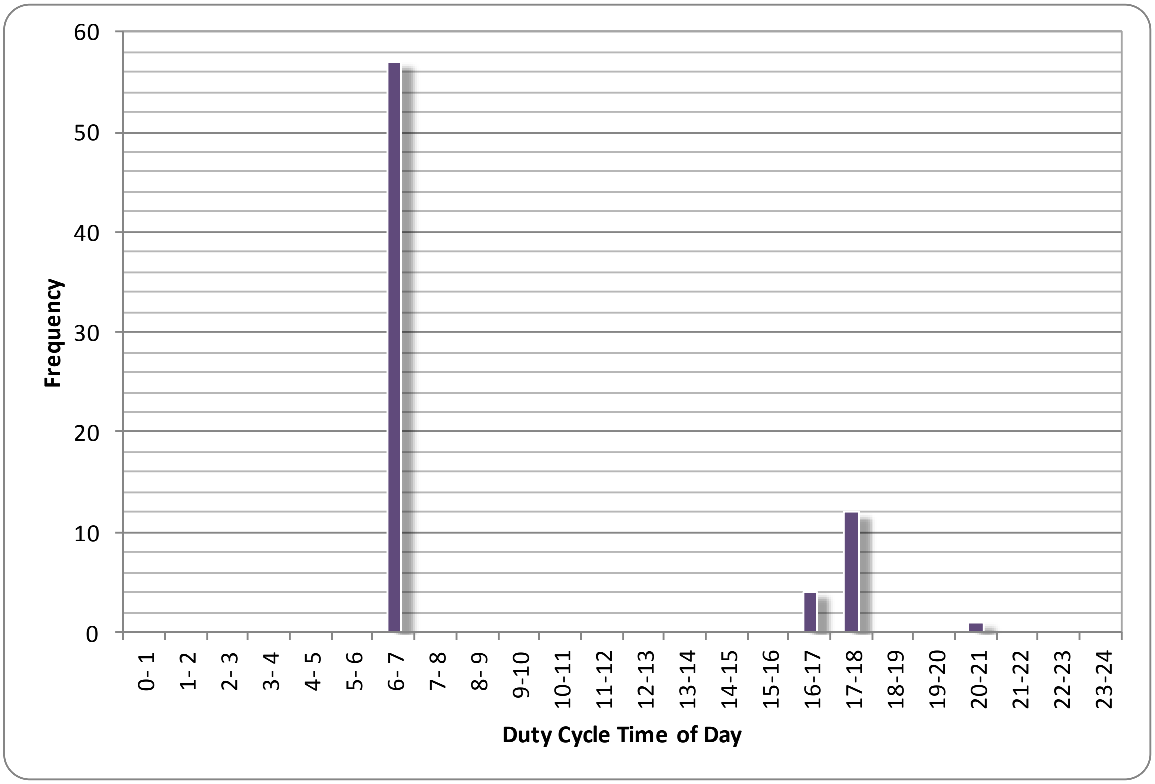

Figure 65. Transit bus highway duty cycle time-of-day frequency distribution.

The duration of the duty cycles ranged from 10.5 to 27.6 min with an average duration of 12.6 min and a standard deviation of 2.71 min. Table 20 presents this and other statistics that define the distributions of these 74 highway duty cycles. One key statistic in the variability of the highway duty cycles is the distribution of minimum speed, which is directly related to congestion. Table 20 shows that there were significant variations in the minimum speed of the duty cycles, mostly due to congestion. The minimum speed ranged from 0.0 to 56.5 mph with an average of 41.5 mph and a standard deviation of 16.2 mph. This statistic presented the highest ratio of standard deviation to mean, indicating a high variability. Graphical representations of the distributions of the duty cycle durations and minimum speeds are shown in Figure 66 and Figure 67, respectively.

Table 20. Transit bus highway duty cycle distribution statistics

Duty cycle parameter distribution statistics	Mean	Standard deviation	Minimum	Maximum	Number of observations
Duration [min]	12.67	2.71	10.51	27.64	74
Average speed [mph]	55.81	7.61	25.04	64.85	74
Standard deviation in speed	5.04	5.90	1.39	26.21	74
Maximum speed [mph]	63.80	3.40	56.54	69.03	74
Minimum speed [mph]	41.52	16.16	0.00	56.50	74

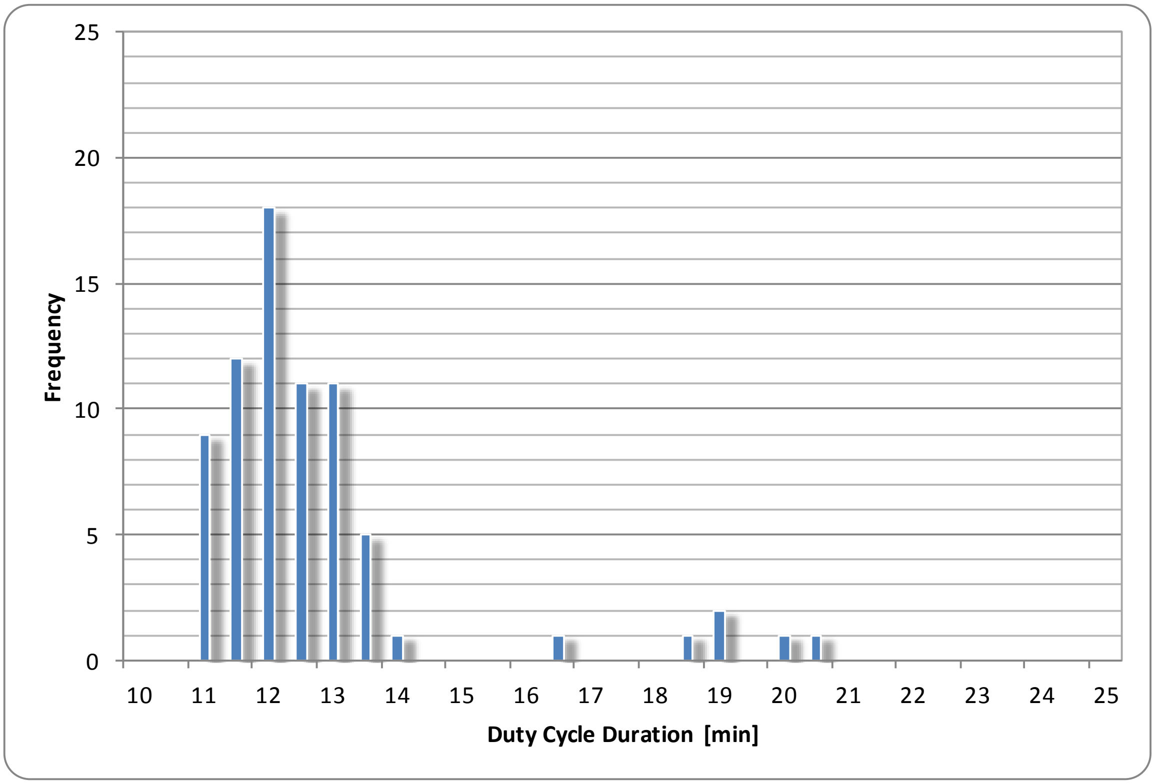

Figure 66. Transit bus highway duty cycle duration frequency distribution.

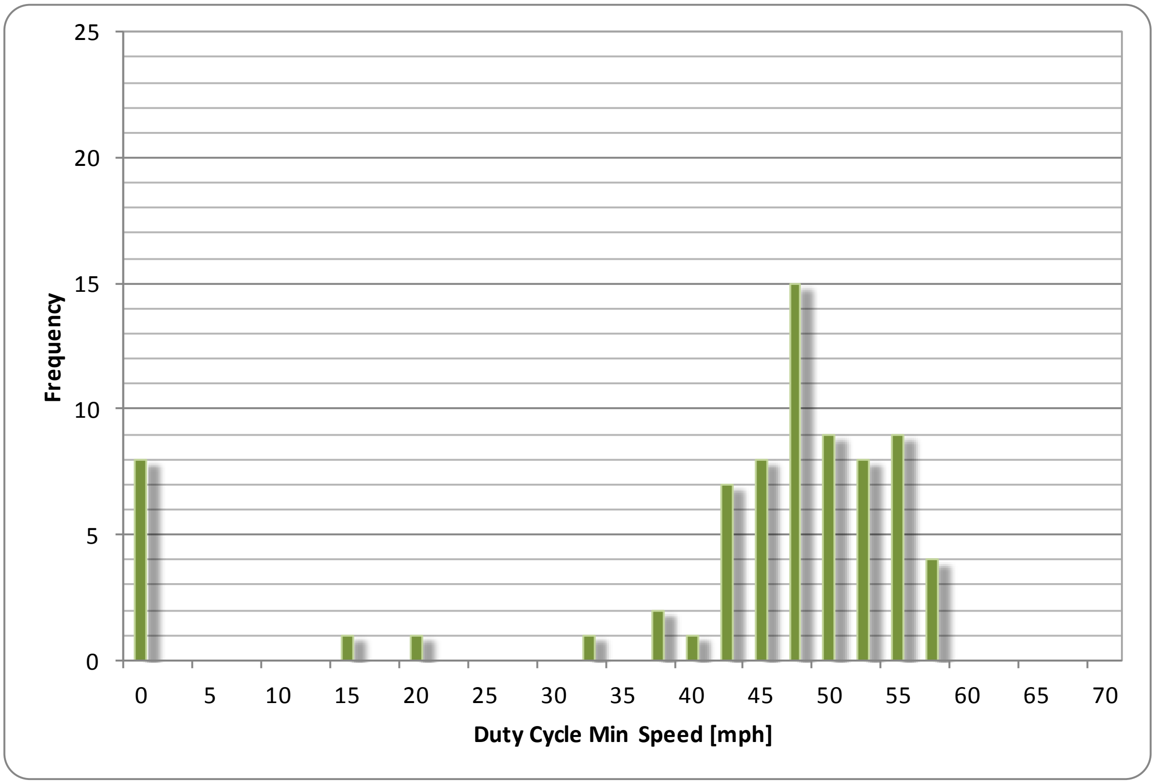

Figure 67. Transit bus highway duty cycle minimum speed frequency distribution.

The 74 duty cycles were ranked in descending order using the duty cycle average speed as the sorting variable. Ten of these duty cycles, the top five and the bottom five, were selected and graphed. The results are presented in Figure 68 and Figure 69, respectively. The top five duty cycles show very little variability in terms of cycle length and shape. The profile of these duty cycles follows the geometric characteristics of the highway in terms of speed, which in this case is almost free-flow speed (highway level of service A). In the case of the bottom five, there is a higher variability in terms of the duty cycle length and also in the shape of the duty cycles. The latter directly reflects the traffic conditions on the freeway.

Taking into account these considerations, and as a first approach for highway duty cycles, the variability in the duty cycle length provides a measure of the duty cycle variability. The speed is a function of the length of the highway segment and the duration of the duty cycle, so the variability of the speed will directly affect the variability of the duty cycle length. The duty cycle variability could be measured by the ratio of the standard deviation of the distribution of duty cycle lengths over the mean of that distribution. For the 74 duty cycles, this ratio is 0.214 (i.e., 2.71 min/12.7 min; see Table 20). For the five top and five bottom duty cycles shown in Figure 68 and Figure 69, the variability was computed at 0.06 and 0.357, respectively. This indicates a skewed distribution of the duty-cycle variability, in which duty cycles are more likely to have high than low variability. Because the demand for public transit increases during peak hours, the bus frequency also increases during these periods. Therefore, a higher proportion of duty cycles were collected under higher traffic-congestion levels, resulting in higher variability in the duty cycles.

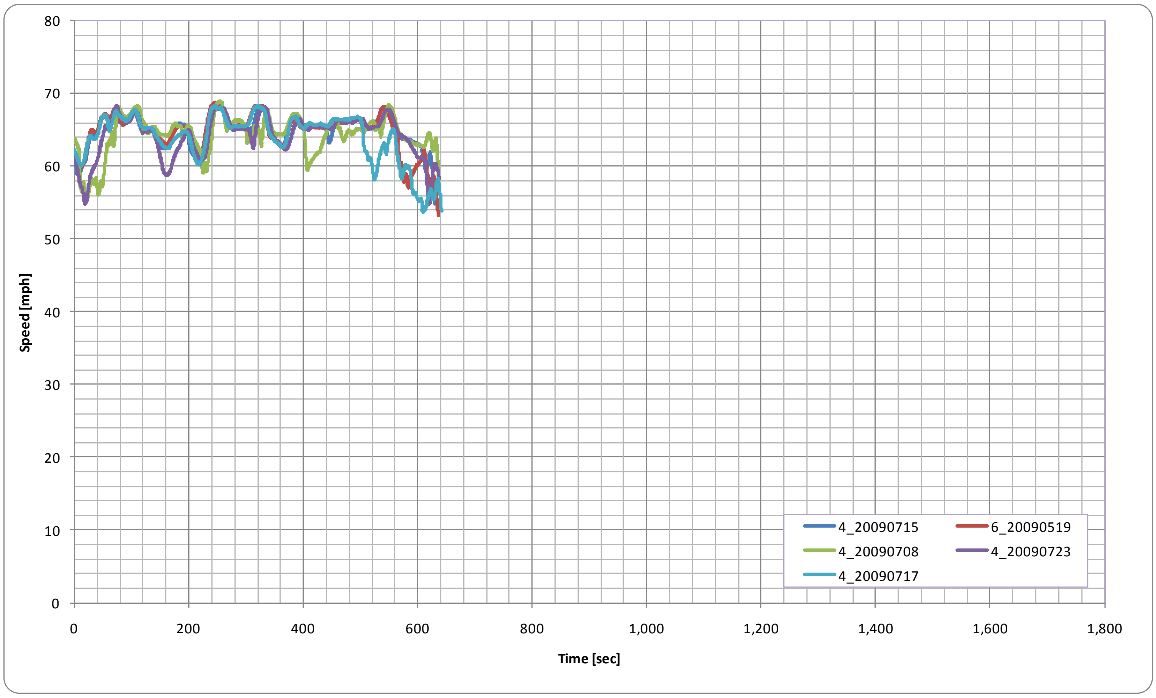

Figure 68. Top five maximum average speed transit bus highway duty cycles.

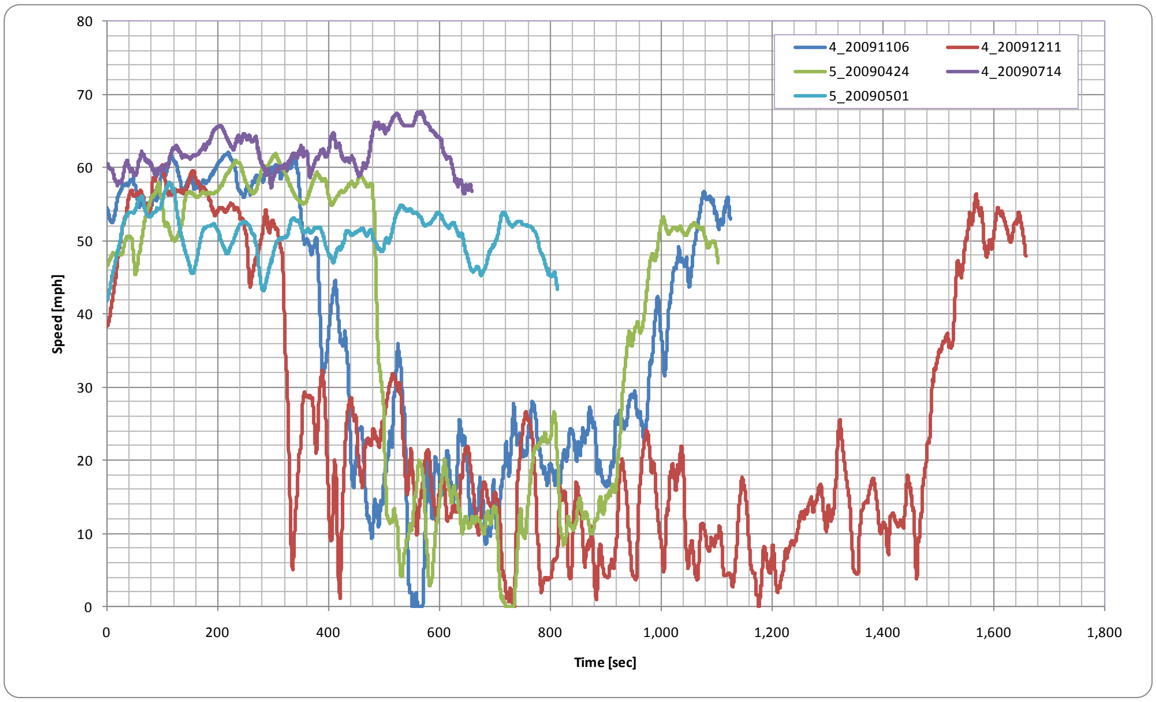

Figure 69. Bottom five maximum average speed transit bus highway duty cycles.

4.5.2 Transit Bus Surface Street Duty Cycles

The first set of duty cycles extracted from the MTDC database focused on surface-street duty cycles. A 4.9 km loop in downtown Knoxville, Tennessee, was selected and the corresponding duty cycles extracted from the database. Figure 70 shows this transit bus route.

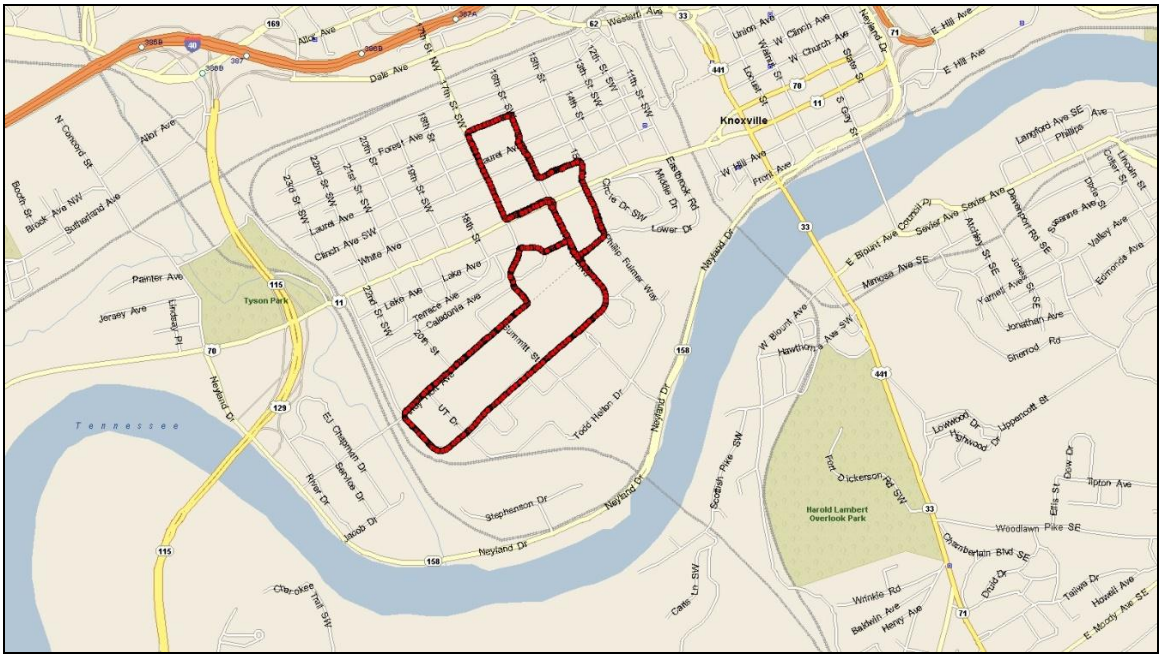

Figure 70. Transit bus surface-street duty cycle route.

Thirty-eight surface-street duty cycles were selected. Their durations ranged from 10.9 to 22.8 min with an average duration of 18.4 min and a standard deviation of 3.29 min. Table 21 presents these and other statistics that define the distributions of these 38 highway duty cycles. Notice that, as opposed to freeway duty cycles, in all of the surface-street duty cycles, the minimum speed was 0.0 mph (i.e., vehicle stationary). A graphical representation of the distribution of the duty cycle lengths is shown in Figure 71.

Table 21. Transit bus surface-street duty cycle distribution statistics

Duty cycle parameter distribution statistics	Mean	Standard deviation	Minimum	Maximum	Number of observations
Duration [min]	18.41	3.29	10.86	22.82	38
Average speed [mph]	9.23	1.89	2.50	13.90	38
Standard deviation in speed	7.49	0.90	5.42	9.34	38
Maximum speed [mph]	26.05	3.06	20.17	31.59	38
Minimum speed [mph]	0.00	0.00	0.00	0.00	38

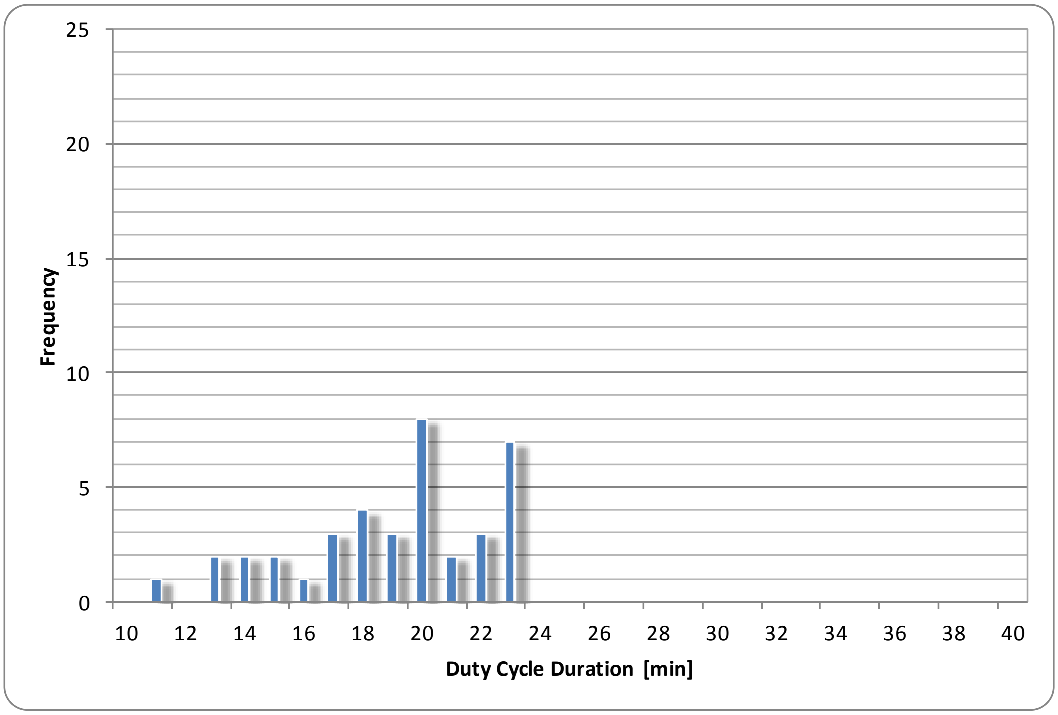

Figure 71. Transit bus surface-street duty cycle duration frequency distribution.

Like the highway duty cycles, the 38 surface-street duty cycles were arranged in descending order using duty cycle average speed as the sorting variable. Ten of these duty cycles, the top five and the bottom five, were selected and graphed. The results are presented in Figure 72 and Figure 73, respectively. Similar to the highway duty cycles, the top five surface-street duty cycles do not show a large variability in terms of cycle duration. For the bottom five, there is a higher variability in duty cycle duration and shape. Using again the ratio of the standard deviation of the distribution of duty cycle duration over the mean of that distribution to estimate the variability of the duty cycles, the 38 duty cycles had a ratio equal to 0.179 (i.e., 3.29 min/18.4 min; see Table 21). For the five top and five bottom duty cycles shown in Figure 72 and Figure 73, the variability was computed at 0.134 and 0.262, respectively. Using this measure, the highway duty cycles presented a higher variability than the surface-street duty cycles (i.e., 0.214 vs. 0.179).

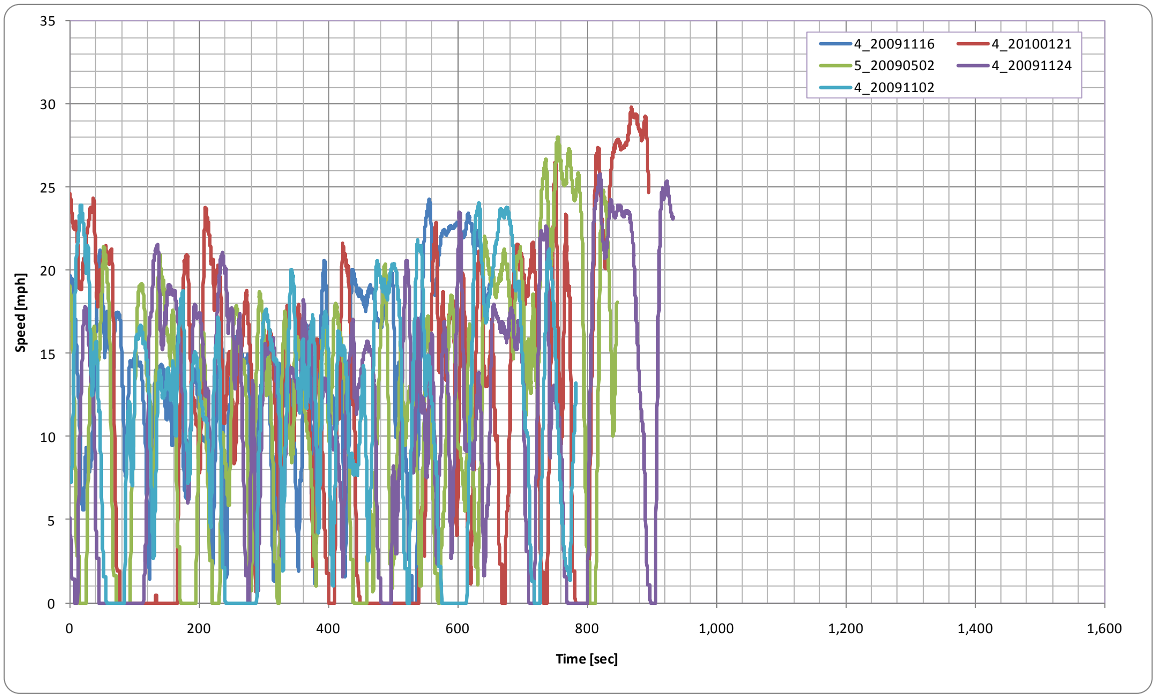

Figure 72. Top five maximum average speed transit bus surface-street duty cycles.

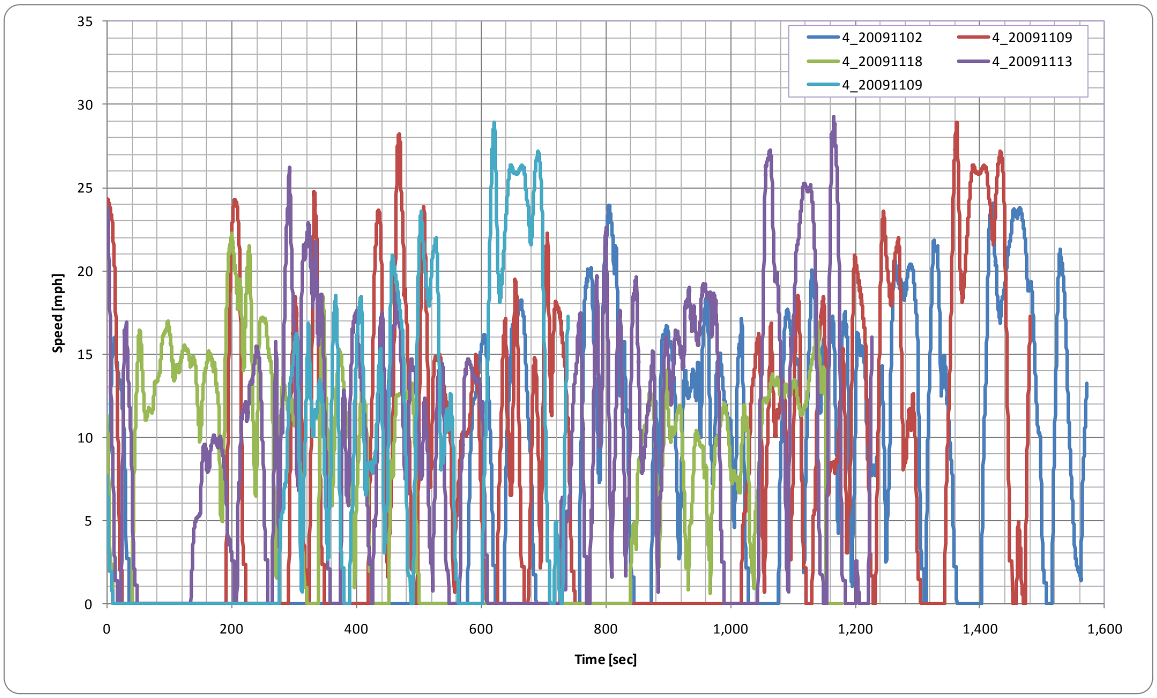

Figure 73. Bottom five maximum average speed transit bus surface-street duty cycles.

4.6 EFFECT OF OPTIMIZED ROUTING ON FUEL EFFICIENCY

The type of operation typical for the combination trucks (MTDC vehicles 1 to 3) participating in this project required the vehicle to be loaded at the warehouse, driven to a series of stops where different deliveries were made, and driven back to the warehouse. The driver chose a route and stopped at the different delivery places, following a certain sequence. The stop sequence and route for each trip were captured by the onboard DAS and characterized by several measures of effectiveness (MOEs), including total driving distance, total fuel consumption, total driving time, and total number of left and right turns. A low-cost mapping and routing software (i.e., Microsoft MapPoint 11) was then used to optimize the route for time while maintaining the original stop sequence, and to optimize the stop sequence and routing. The same MOEs were computed and used to compare the three alternatives in order to determine the impacts of using route optimization on FE for this vocation.

4.6.1 Original Stop Sequence and Routing

Thirty-one trips were selected at random from the database of trips collected by the local delivery vocation trucks participating in the project (11 for MTDC vehicle 1, and 10 for the other two vehicles). For each of these trips, stops that lasted for more than 10 min were identified (i.e., their latitude and longitude extracted from the database) and manually corroborated to determine if they were delivery stops. Those stops were then mapped using Microsoft MapPoint 11, together with the route that the driver followed during the delivery trip. Figure 74 shows a screen capture for one of the MTDC vehicle 2 trips. The stops are shown as yellow rectangles (there were 18 stops, counting the start and end of the trip at the warehouse, not shown on the map), the driver’s route marked with red bubbles, and the route used by the software shown in blue. The original stop sequence is presented in Table 22, where the numbers in column 2 show the order in which the stops were made.

Table 22. Original and optimized stop sequences

Stop ID	Original sequence	Optimized sequence
S1	1	1
S2	2	2
S3	3	9
S4	4	7
S5	5	8
S6	6	6
S7	7	3
S8	8	4
S9	9	5
S10	10	11
S11	11	10
S12	12	12
S13	13	14
S14	14	13
S15	15	15
S16	16	16
S17	17	17
S18	18	18

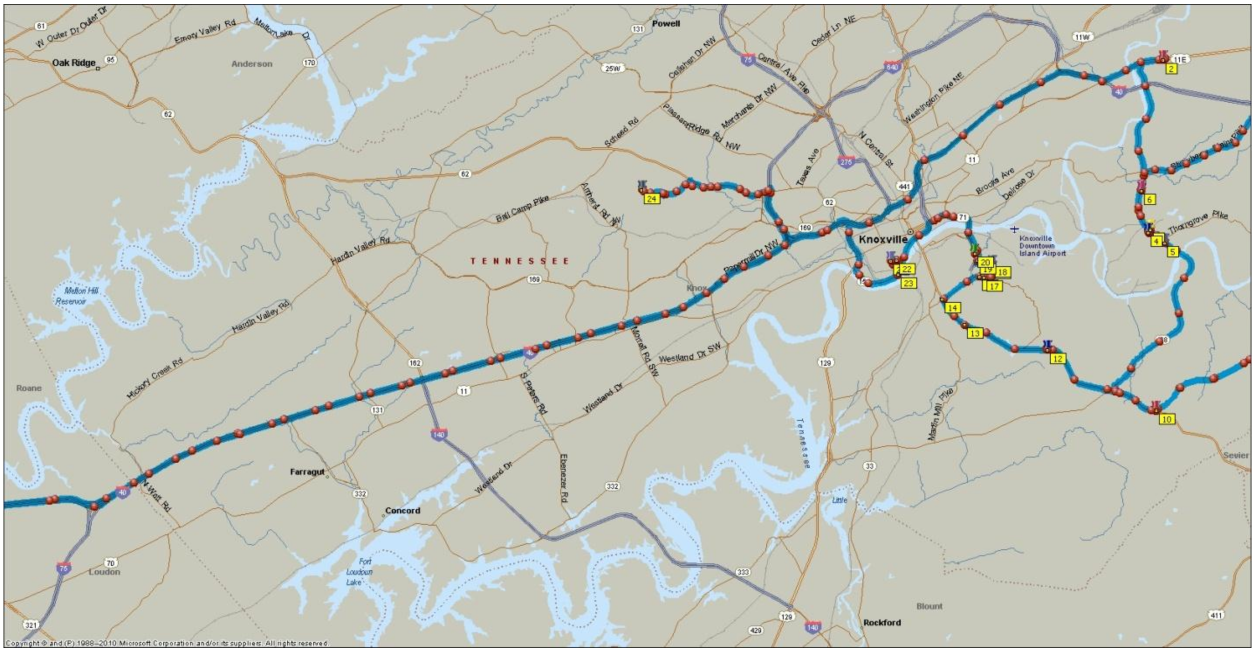

Figure 74. Driver's selected route and stop sequence.

The software, which was forced to adhere to the route and stop sequence followed by the driver, provided the driving time, driving distance, and total number of left and right turns; fuel consumption was calculated using the driving distance and average FE of each of the three vehicles (see Table 14). Although driving time, driving distance, and fuel consumed while driving could have been computed using the information collected in the FOT, the measures provided by the software were used so they can be compared fairly against the measures characterizing the other two alternatives that were not in the database.

4.6.2 Original Stop Sequence and Optimized Routing

The constraint to adhere to the driver's selected route was then relaxed and the software was used to determine an optimized route (according to its internal optimization algorithms) that followed the original sequence of stops. This optimized route is presented in Figure 75. In this figure, the dots indicate the actual route, and the blue line indicates the software-recommended route. Notice there were some places (shown inside a circle in the figure) in which there was disagreement between the original route and the optimized route. In general, the route selected by the software resulted in shorter driving distances and time, although there were a few instances in which that were not the case.

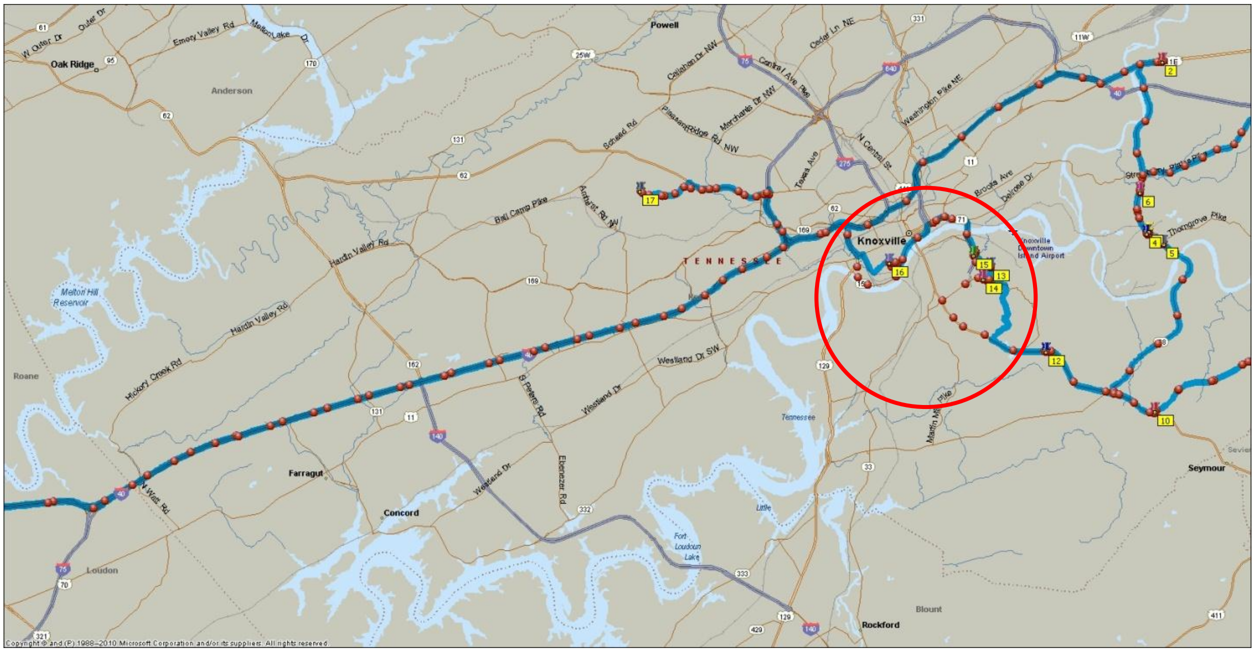

Figure 75. Original stop sequence with optimized route.

Table 23 presents a summary of the relative differences in terms of the MOEs studied. On average, software-optimized routing that maintained the original sequence of stops produced improvements in all of the measures considered, which in some instances were substantial. However, in 4 cases of the 31, the driver did better than the software in terms of driving distance (and associated measures such as fuel consumed and number of left and/or right turns). The software always did better in terms of driving time because that was the objective of its route-optimization algorithm.

Table 23. Driver vs. optimized route w/original stops—all vehicles (MTDC 1-3)

Statistics	Delta driving time		Delta driving distance		Delta fuel consumption [gal]	Delta turns	
	[min]	[%]	[mile]	[%]		Left [%]	Right [%]
No. of observations	31	31	31	31	31	31	31
Minimum	0	0.0%	−1.3	−1.0%	−0.2	−13.3%	−12.5%
Maximum	24	8.9%	20.7	9.3%	2.6	23.1%	27.3%
Mean	3	1.8%	2.3	1.6%	0.3	4.4%	2.2%
Std. dev.	5	2.7%	4.4	2.6%	0.6	10.6%	7.9%

The information summarized in Table 23 is also presented in more detail in Figure 76 and Figure 77, which show the distributions of fuel savings and time savings for the case in which the original sequence of stops is maintained and the route is optimized.

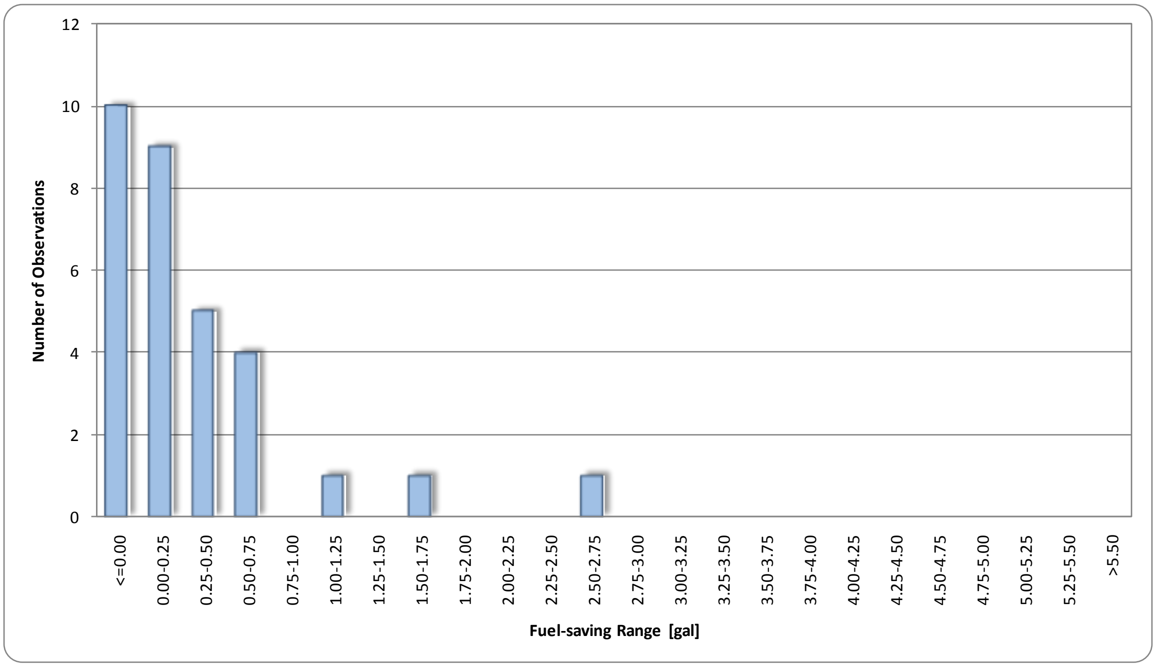

Figure 76. All vehicles (MTDC 1-3) driver vs. route optimization with original stop sequence: fuel savings.

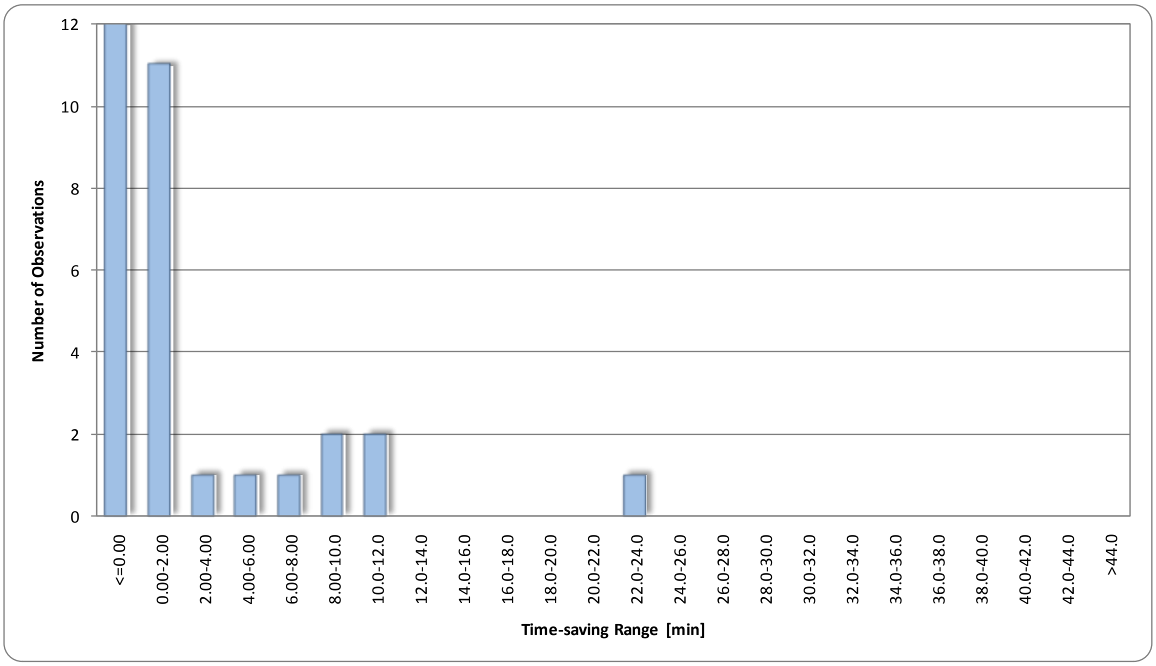

Figure 77. All vehicles (MTDC 1-3) driver vs. route optimization with original stop sequence: time savings.

4.6.3 Optimized Stop Sequence and Routing

The routing software was also used to optimize the sequence of stops and then optimize the route. Table 22 presents the optimized sequence of stops (third column of the table) and Figure 78 shows the

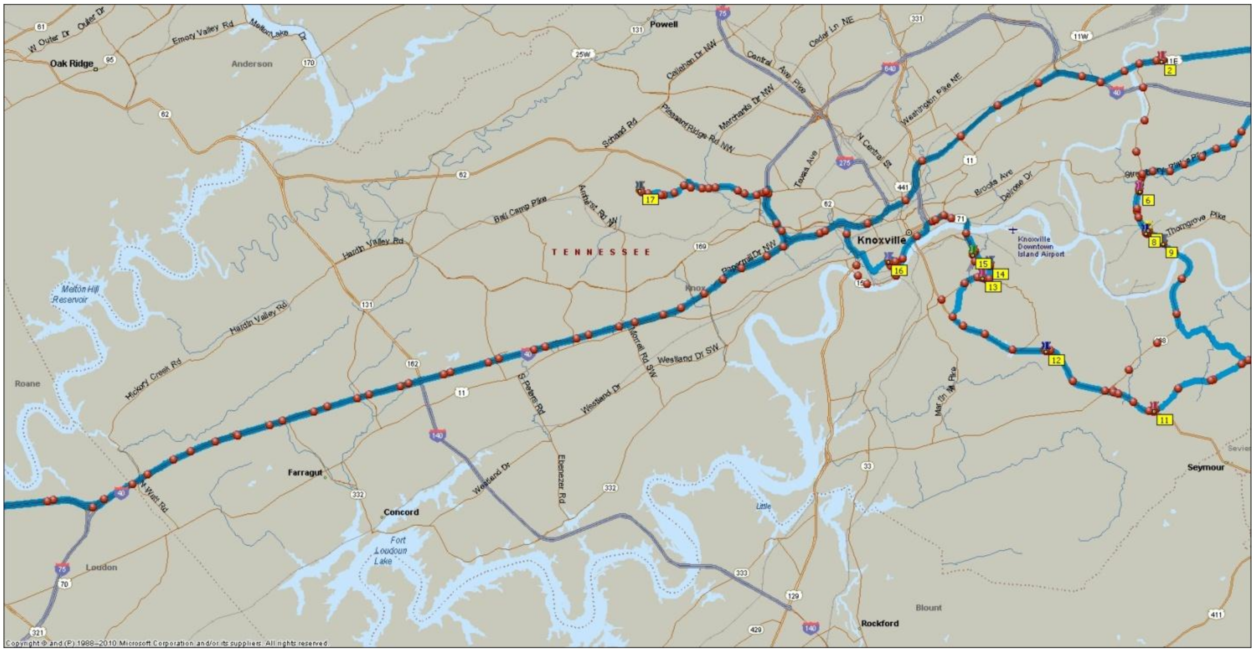

Figure 78. Optimized stop sequence and route.

optimized route for the particular vehicle 2 trip used as an example. The route is the same as the one shown in Figure 75, but the stops are visited in a different sequence.

Summary results of the comparisons between the two alternatives (i.e., original vs. optimized stop sequence and routing) are presented in Table 24. For driving distance, driving time, and fuel consumed, the optimized stop sequence and route alternative always proved better than or equal to the original alternative (i.e., driver-selected route and stop sequence). Only in one case out of 31 did the two alternatives show the same MOEs; however, in the other cases, the fuel savings and time savings were as high as 25% and 30%, respectively. Figure 79 and Figure 80 illustrate in more detail these gains in terms of fuel and time saved, respectively.

For the remaining measure (total number of left and right turns, a measure of safety since left turns are in general more dangerous than right turns), the optimized alternative was worse in six out of 31 cases. But in the other 25 cases it reduced the number of left turns by up to almost 45%.

Table 24. Driver vs. optimized stop sequence and route—all vehicles (MTDC 1-3)

Statistics	Delta driving time		Delta driving distance		Delta fuel consumption [gal]	Delta turns	
	[min]	[%]	[mile]	[%]		Left [%]	Right [%]
No. of observations	31	31	31	31	31	31	31
Minimum	0	0.0%	0.2	0.1%	0.0	−57.1%	−40.0%
Maximum	42	25.1%	36.9	29.7%	5.1	45.0%	47.1%
Mean	15	10.7%	10.5	9.4%	1.4	12.3%	6.5%
Std. dev.	10	6.2%	8.3	6.4%	1.2	24.1%	20.1%

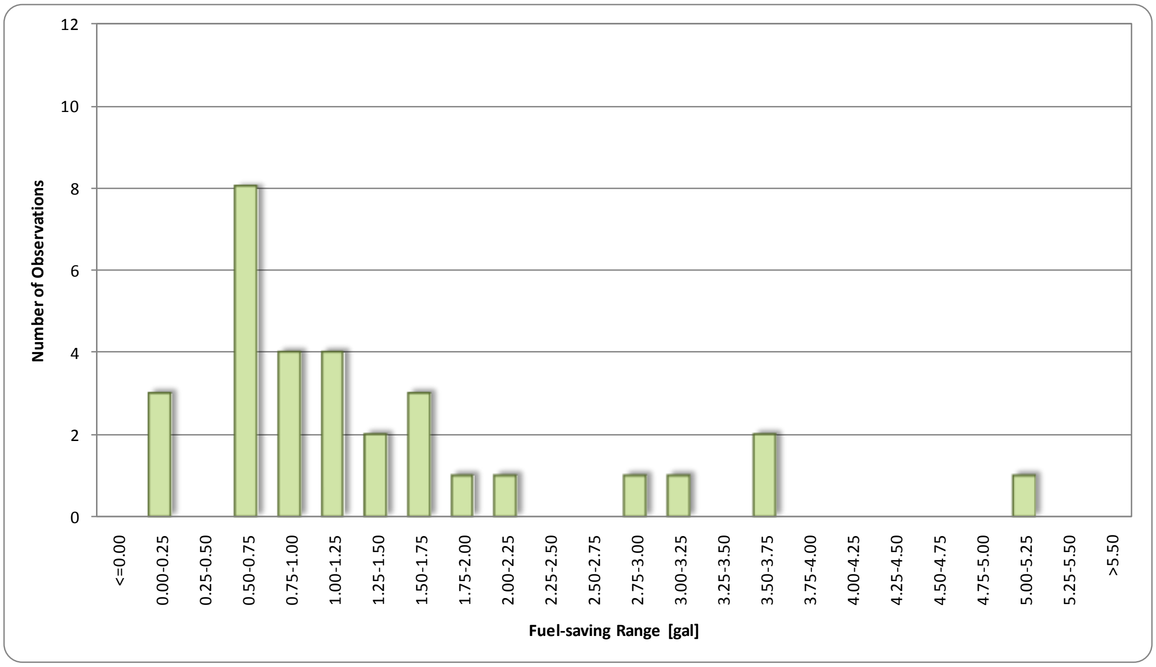

Figure 79. All vehicles (MTDC 1-3) driver vs. stop sequence and route optimization: fuel savings.

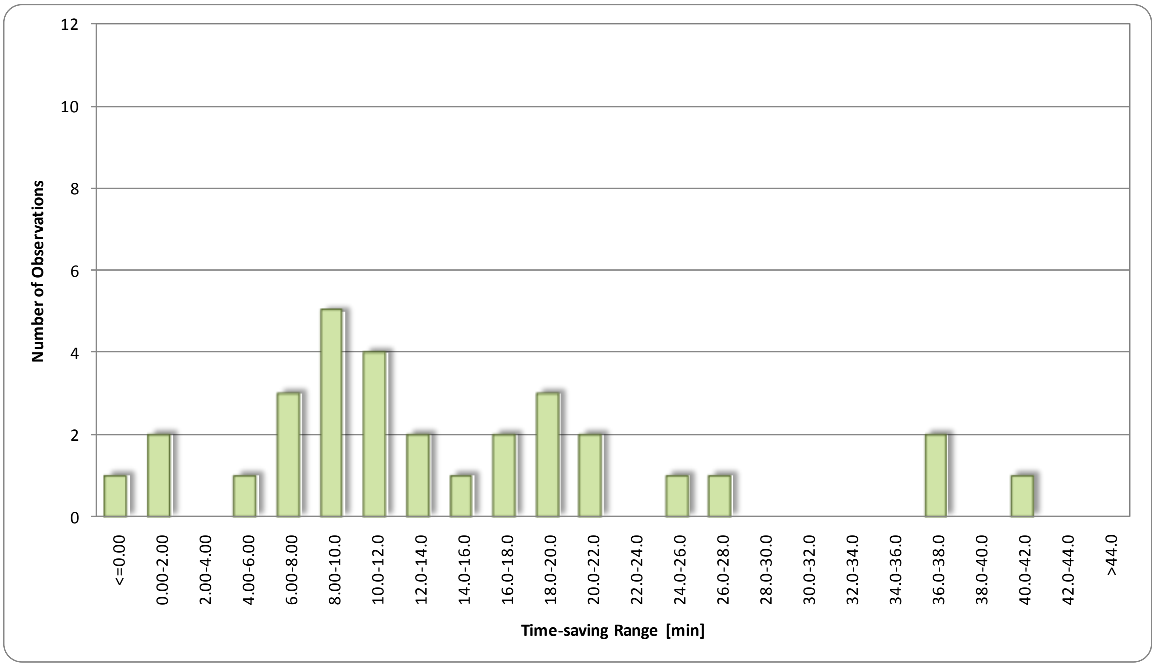

Figure 80. All vehicles (1-3) driver vs. stop sequence and route optimization: time savings.

In conclusion, routing software (even inexpensive software like that used for this analysis) can potentially provide significant benefits in terms of time and fuel saved for operations that involve many stops within a single trip.

4.7 SAFETY SENSOR DATA

Beyond the standard duty cycle data collection system required for the MTDC project, additional sensors were installed on three test vehicles (Class-7 combination delivery vehicles) to collect several safety-related signals of interest to FMCSA. These additional sensors were provided through a partnership with FMCSA. The real-time brake stroke, tire pressure, and weight information obtained from these sensors is expected to make possible a number of safety-related analyses, such as determining the frequency and severity of braking events and tracking tire pressure changes over time. Because these signals are posted to the vehicle's data bus, they also have the potential to be read by onboard telematics solutions for inclusion in other FMCSA efforts such as the Wireless Roadside Inspection (WRI) Program. Because of the "drop and hook" operation of the host carrier, instrumentation was not installed on any of the carrier's trailers. Although ORNL's primary task was collecting the data rather than performing any analyses, a preliminary analysis of the safety sensor data was performed to determine how the sensors had functioned during the data collection period and to explore the types of information available from this expanded data set.

4.7.1 Findings from Safety Sensors

Each sensor provided useful information related to the duty cycle of the vehicle and/or the effectiveness of the sensor. Unless otherwise specified, the following results are based on analysis of the data compiled from all three combination test vehicles instrumented with safety sensors. This data represents approximately 45,000 miles of local delivery duty cycle data.

4.7.1.1 Electronic Brake Stroke Monitoring System

Four brake stroke sensors were installed in each vehicle, one at each wheel end of the tractor. The in-cab unit provided the driver audible alerts of out-of-stroke conditions. In addition, a brake system pressure transducer provided information about braking events in the duty cycle data. The brake stroke system provided real-time status codes for each wheel position. A histogram of these codes is shown in Figure 81.

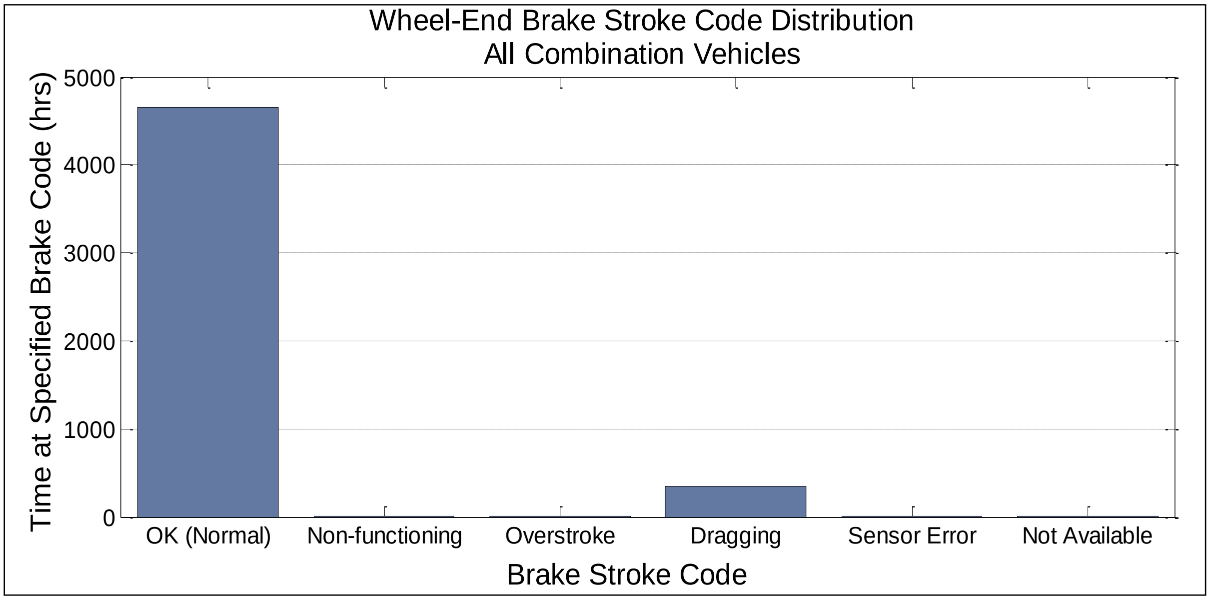

Figure 81. Distribution of brake stroke status codes.

From the time the systems were first installed, one sensor continually output a dragging brake code. The manufacturer was not able to correct this error, and the team decided to proceed with the FOT with plans to discard data from this sensor. This errant reading yielded an overall error of 6% (for all three vehicles).

The brake system pressure transducer provided information about the overall brake application pressure, identifying braking events in the duty cycle data. The chart shown in Figure 82 illustrates the low percentage of time the test vehicles were engaged in braking events.

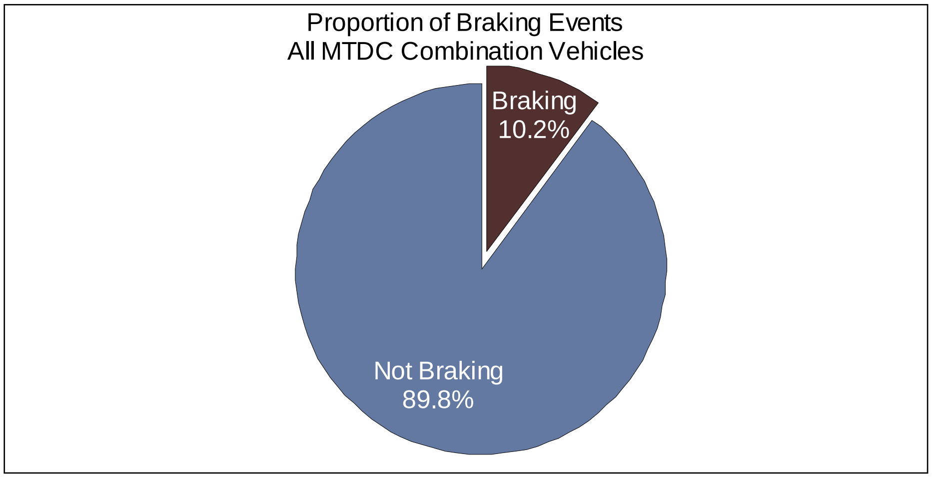

Figure 82. Proportion of braking events in MTDC combination vehicle duty cycles.

Of interest to FMCSA is the frequency of hard braking events, characterized by higher brake application pressures. The data collected in this FOT indicates that lower-pressure braking events were far more common than hard braking events. From the distribution of brake application pressure for the collected data (Figure 83), it is evident that the brakes are nearly always applied at pressures below 30 psi.

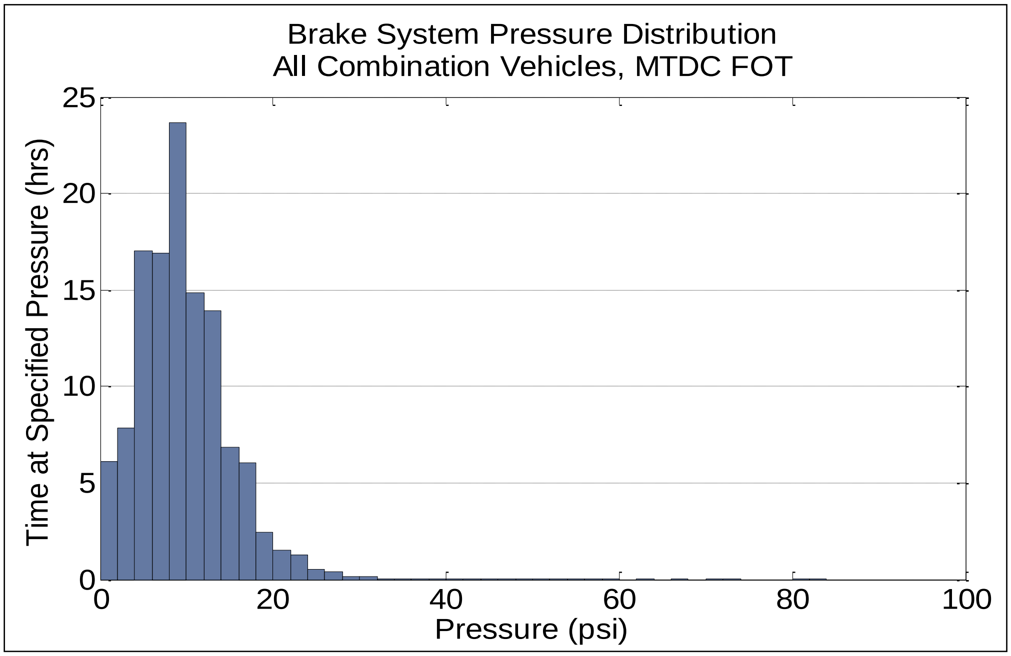

Figure 83. Distribution of brake application pressure for MTDC combination vehicles.

The pressure signal provided by this sensor was reliable, with no detected problems. The time history of this signal, taken in conjunction with the vehicle speed, can be used to examine specific braking events. Figure 84 shows a 2,000-s section of duty cycle data from one of the test vehicles in which there were several braking events. In this figure, it is apparent that significant decreases in vehicle speed (green trace) are caused by braking events, indicated by increases in brake application pressure (blue trace).

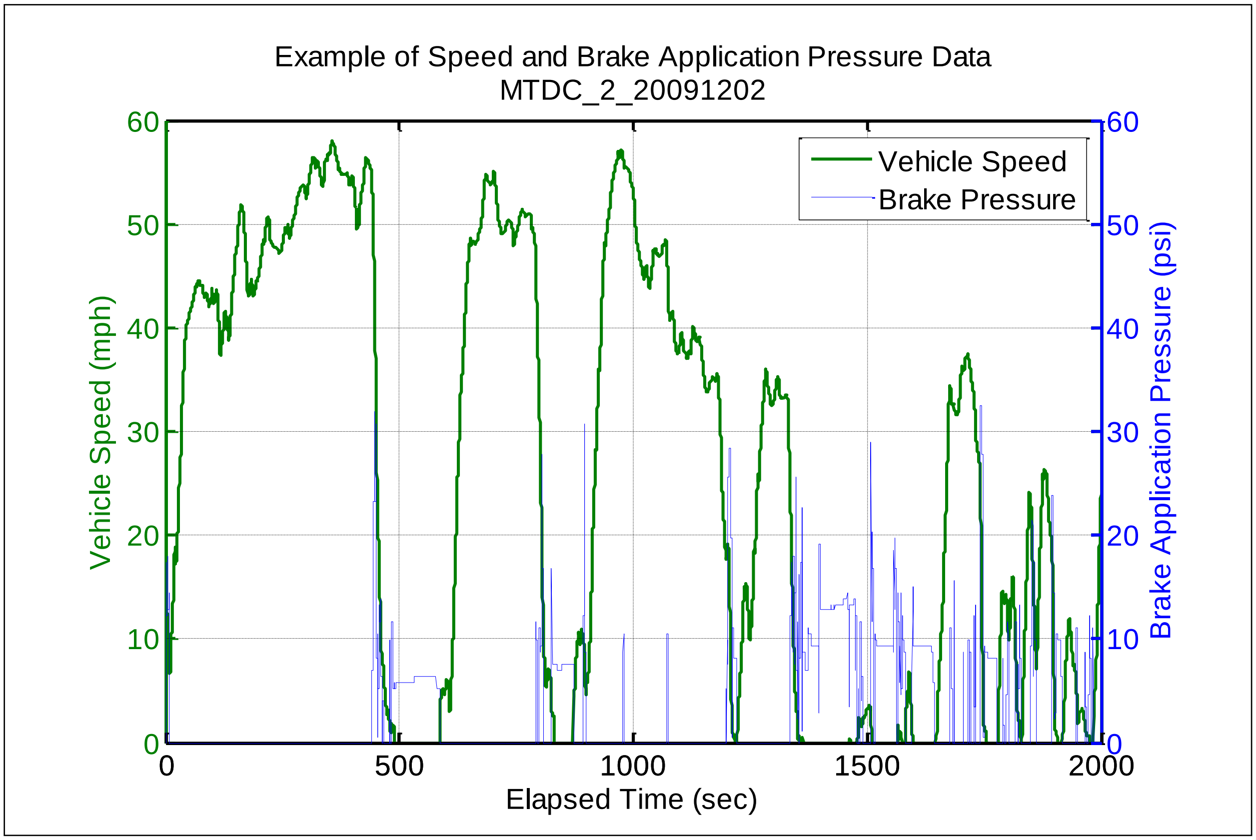

Figure 84. Sample time history of speed and brake application pressure (vehicle 2).

4.7.1.2 Tire Pressure Monitoring System

The TPMS included a combination pressure/temperature sensor for each tractor tire for a total of six sensors per vehicle. An in-cab display provided the driver with the temperature and pressure for each tire and an audible alert for out-of-range values indicative of a problem (e.g., a tire with low tire pressure). Because the partnering fleet checked the tire pressures weekly, no out-of-range values were expected to be encountered (except as a result of tire damage). The distribution of tire pressure for one tire position of one of the test vehicles is shown in Figure 85. This histogram indicates sensor values were in range most of the time, although out-of-range values did occur and several flags were set (Figure 86).

When a tire pressure reading was outside of the acceptable (no warning) range as defined in Table 25, the TPMS generated a corresponding error code for that tire (Figure 86). The driver investigated the error codes generated but did not identify any problems during the course of the FOT. During this interval, the error or alert rate for the TPMS represented more than 20% of the data collected.

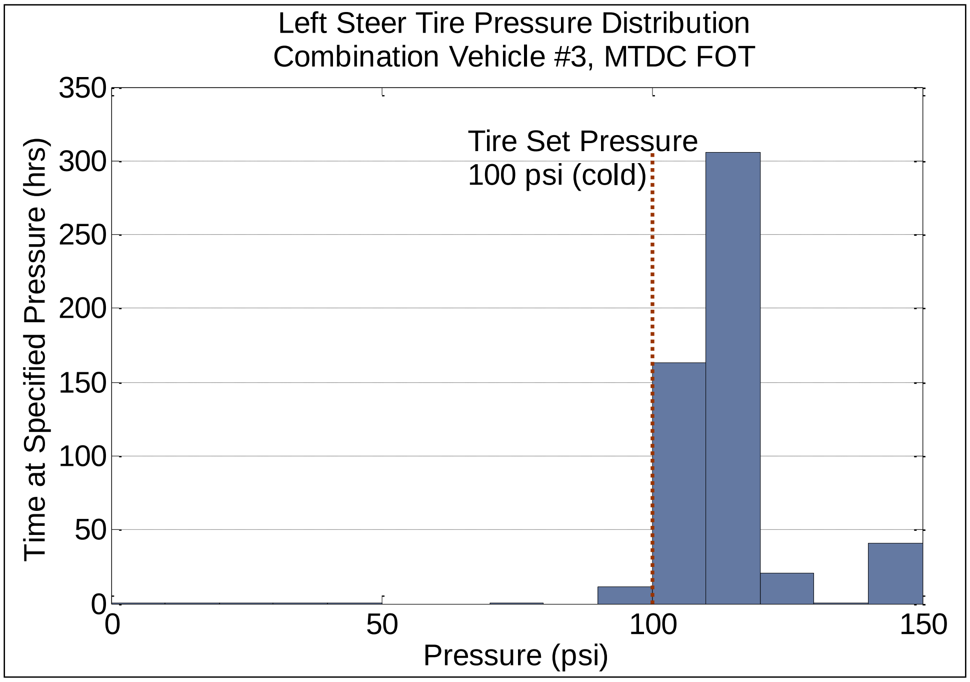

Figure 85. Tire pressure distribution.

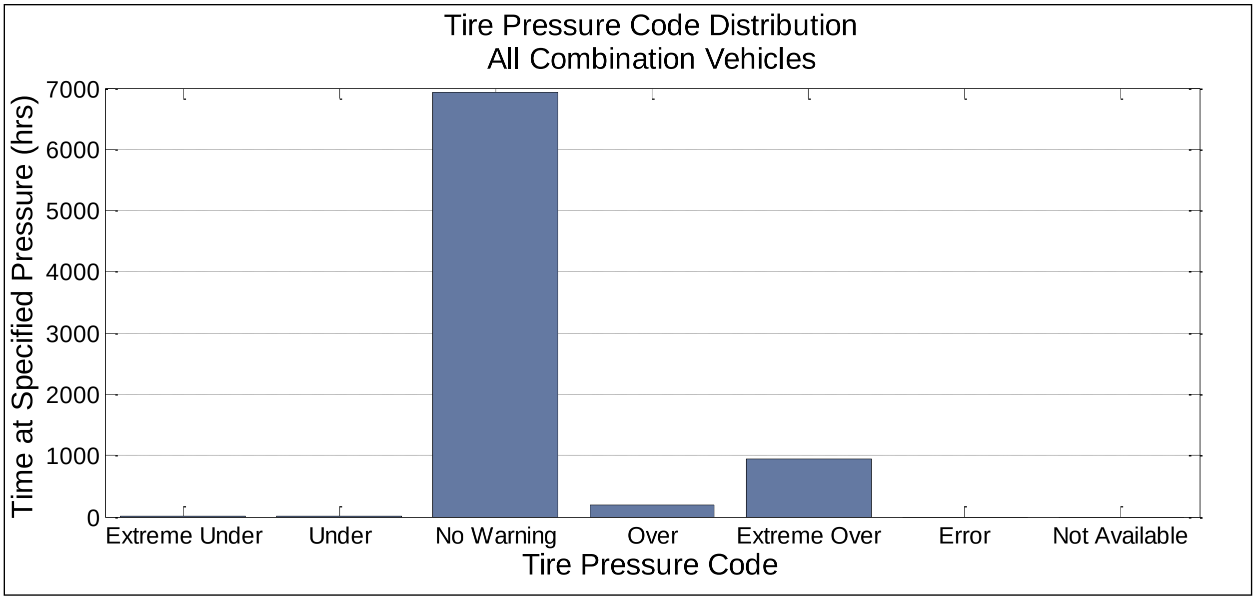

Figure 86. Distribution of tire pressure threshold detection codes.

Table 25. Pressure ranges for TPMS status codes

Pressure status code	Corresponding range
Extreme over pressure	Over 145 psi
Over pressure	125-145 psi
No warning	75-125 psi
Under pressure	50-75 psi
Extreme under pressure	Below 50 psi

Each tire pressure sensor also had temperature-reading capability. A histogram of this data is shown in Figure 87.

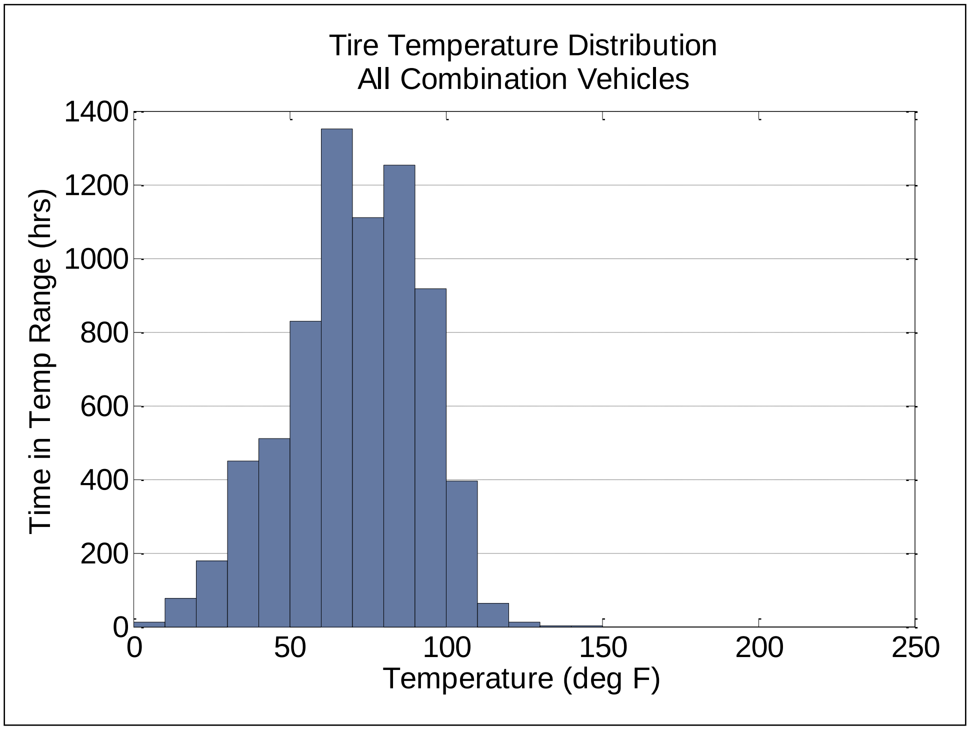

Figure 87. Tire temperature distribution.

Researchers, drivers, and maintenance technicians reported a number of additional problems associated with the TPMS throughout the FOT, such as nonfunctioning sensors, confusion of wheel positions reported, significant temperature differences between wheel positions at a given time, and discrepancies between the in-cab display and the values reported on the data bus.

4.7.1.3 Vehicle Self-Weighing System

The self-weighing system reported drive and steer axle weights based on a sensor in the vehicle's air suspension system. Although readings were taken continuously, the system was not designed for accuracy while the vehicle was moving; ORNL has a preliminary algorithm to infer actual weights from reported values o the instrumented axles (Section 4.5). The reported weights are in the range expected for Class-7 vehicles (up to 12,000 and 20,000 lb, respectively) for the steer and drive axles (Figure 88 and Figure 89), with very few out-of-range values reported. As expected, the drive axle weight readings were fairly constant.

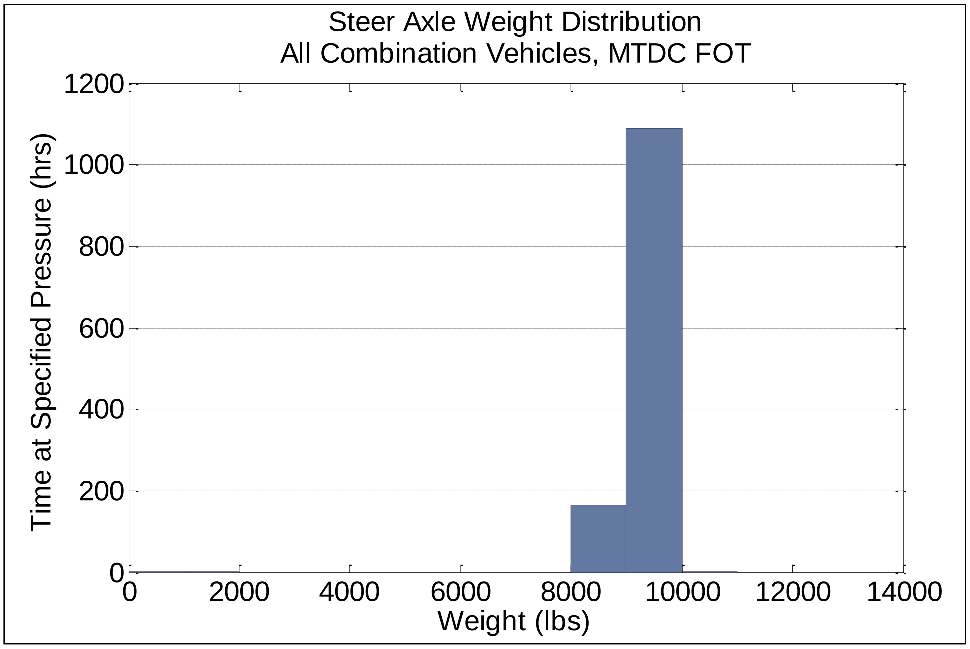

Figure 88. Distribution of steer axle weights.

Although this system was not designed for accuracy while the vehicle was moving, unloaded and loaded approximate weights can be identified in the drive axle group weight distribution shown in Figure 89.

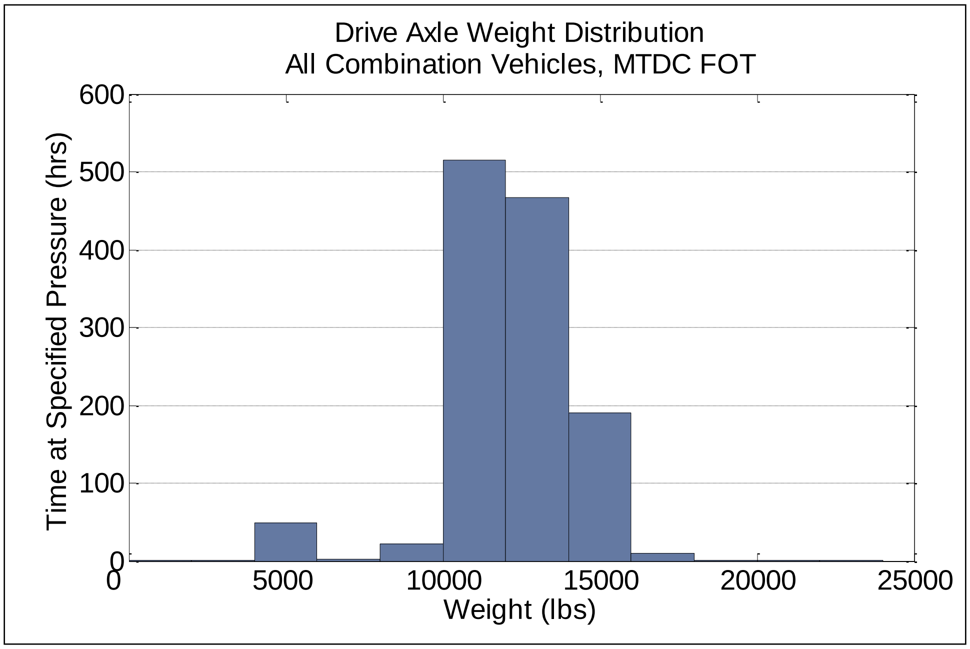

Figure 89. Distribution of drive axle weights.

4.7.2 Implications for Research

4.7.2.1 Post-Processed vs. Real-Time Data

Because of the number of errors present in the brake stroke and TPMSs, this data requires additional post-processing to filter out the errors before further analysis can be conducted. This is not expected to cause difficulty for non-real-time uses such as determining the number and severity of braking events in a given duty cycle.

Although the vehicle self-weighing system was not designed to report accurate weights for a vehicle in motion, streaming data from this system was sufficiently accurate to estimate loading (e.g., unladen, medium load, fully laden). After completion of the weight prediction algorithm, post-processing could be used to achieve more resolution from these signals.

From the errors in the TPMS and brake stroke system, it is evident that post-processing based on an interval of data is required before the data can be used. However, the brake application pressure transducer portion of the braking system sensors did seem to provide reliable, useful data. Real-time use of data from the self-weighing system is suitable only for general estimates of the weight (e.g., as an indicator that the vehicle is lightly laden). This limitation does not preclude near-real-time uses involving onboard processing.

4.7.2.3 Specific Applications of Data

The positive results obtained from the brake application pressure sensors have led to follow-on research in FY 2011 for ORNL in FMCSA's Real-Time Dynamic Brake Assessment project.[17] This effort built on the sensor work done in the Part 1 MTDC FOT, using a modified brake application pressure sensor on one of the instrumented vehicles to further study low-pressure braking events. The proof-of-concept testing examined the feasibility of an onboard brake assessment tool based on real-world driving data, such the braking event shown in Figure 90.

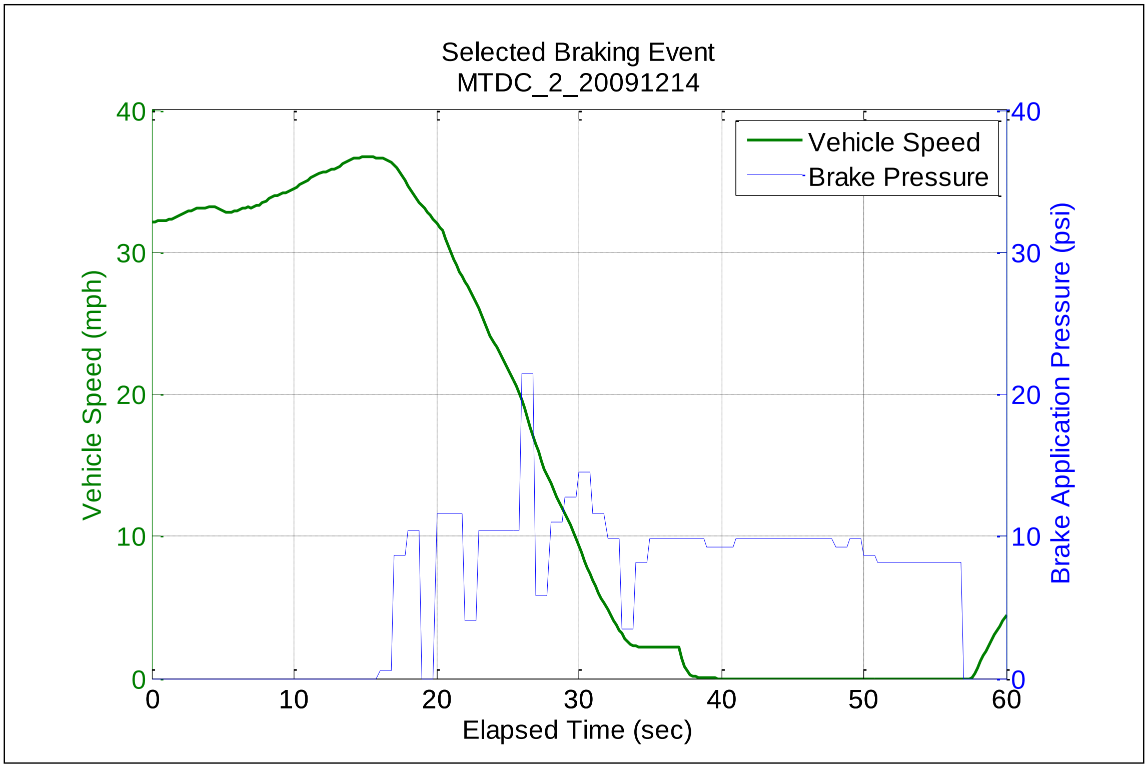

Figure 90. Selected braking event.

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[17] Lascurain, M.B., O. Franzese, and G. J. Capps, *Real-Time Dynamic Brake Assessment Proof of Concept Final Report*, Oak Ridge National Laboratory, 2011. http://info.ornl.gov/sites/publications/Files/Pub33488.pdf

Because all the safety sensors studied posted data to the vehicle’s data bus, and therefore have the potential to be read by any onboard system, one potential use of the data involves inclusion in the Safety Data Message Set for FMCSA’s WRI program. Although these sensors can provide valuable advisory information, it is recommended that, at this stage, data from such safety sensors not be used to flag WRI test vehicles for further inspection for several reasons:

- “False alarms” and sensor errors were consistently present in one of the brake stroke monitoring systems.
- There were a number of errors and discrepancies between the in-cab and data bus reported readings for the TPMS data.
- The self-weighing system was designed for static weighing on level ground with the brake released, not over-the-road, instantaneous weight measurements.

5. ANALYSIS OF THE PART 2 FOT DATA

In Part 2 of this project, three utility vehicles from the KUB fleet and three towing and recovery trucks from the FCWS company were selected and instrumented with the same DAS equipment used in Part 1 of the project. The DAS collected 70 channels of data during approximately 1 year at a rate of 5 Hz. The KUB fleet operates within an East Tennessee region covering a 688 sq mile area that includes the Tennessee counties of Knox, Union, Grainger, Jefferson, and Sevier. The company serves 196,499 customers and maintains 5,238 miles of service lines and 59 substations[18]. Figure 91 shows the spatial coverage of the three utility vehicles that participated in this project. The FCWS operates mainly in the East Tennessee area, although in a few cases the participating towing and recovery trucks traveled to adjacent states and even farther. The area of operation of the towing and recovery trucks while participating in this project is shown in Figure 92.

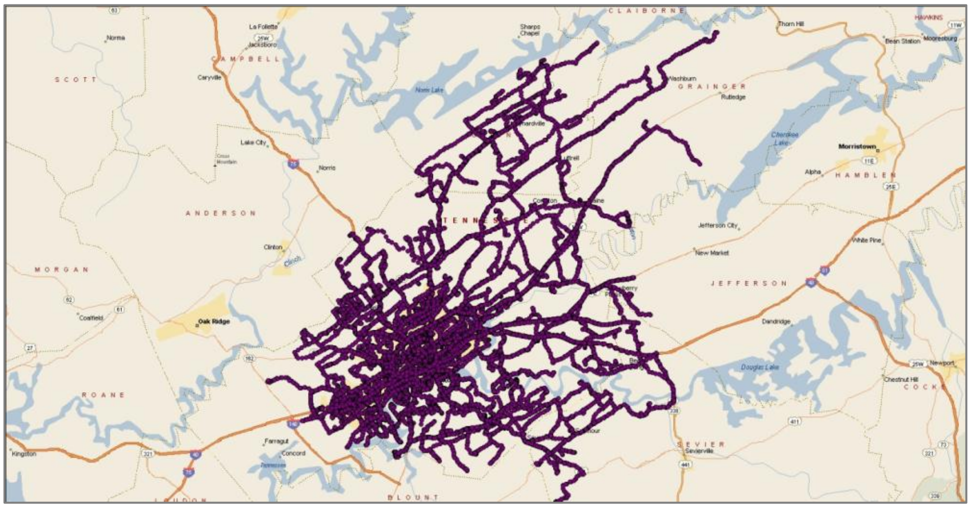

Figure 91. Routes of participating KUB utility vehicles (east Tennessee area).

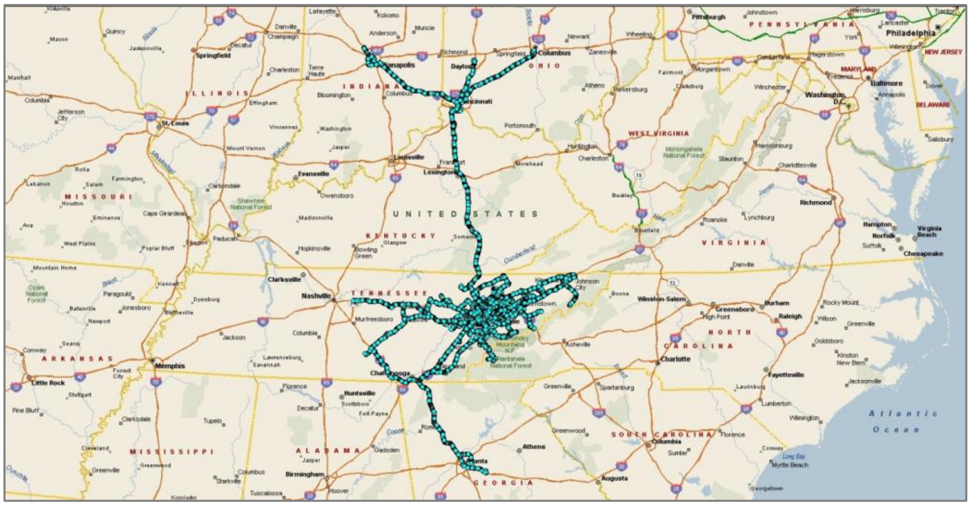

Figure 92. Routes of participating FCWS towing and recovery trucks (Tennessee and adjacent states).

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[18] See http://www.kub.org

The data collected in the second phase of this project was similar to the data gathered in Part 1. It included information on engine speed, fuel rate, gear ratio, vehicle speed, PTO operation, and other data read from the vehicle's data bus; spatial information such as latitude, longitude, and altitude acquired from an onboard GPS device; and instantaneous steer and drive axles weight for the towing and recovery trucks. The weight information was gathered from devices mounted on the vehicles; two of them consisted of strain gages, and the third vehicle was instrumented with an air-bag pressure transducer. Over the duration of the Part 2 MTDC FOT (about 16 months), the three utility vehicles logged nearly 18,000 miles, and the three towing and recovery trucks traveled 70,000 miles.

This section describes the results of the data analysis performed with the information collected in the Part 2 MTDC FOT. Section 5.1 presents a description of the data cleansing process and the organization of the extensive information collected in this part of the project. Following that, a discussion is provided regarding additional models developed to complement the data collected (e.g., the algorithms used to filter and cleanse the collected vehicle weight information). Those models were developed using the data gathered in the project and, where applicable, these models were used to fill in the gaps for those unusual cases in which a particular channel of information was not collected.

The results of the analysis are subsequently presented, starting with some general statistics and followed by comparisons of the average FEs observed from vehicles operating with different payload levels. An assessment and comparison of the PTO usage and fuel consumption is also presented for both the utility vehicles and the towing and recovery trucks. Finally, the section includes an analysis of the distribution of the frequency and length of stops of the four vocations that participated in the MTDC project.

5.1 DATA AND ORGANIZATION

Similar to the information collected in Part 1 of the MTDC FOT, the data gathered in Part 2 was organized, checked for accuracy (and errors corrected and/or marked), and stored in a database in preparation for the data analysis and distribution of information. The field tests conducted in the second part of this project (more than 70 channels of data collected at 5 Hz for six vehicles) produced a database of 130 GB of uncompressed information (see Table 26 and Table 27). Overall, the MTDC project collected 320 GB of uncompressed data (190 GB for Part 1 of the MTDC FOT and 130 GB for Part 2 of the MTDC FOT).

Table 26. Size and number of data files generated in the project—utility vehicles

	MTDC vehicle			Grand total
	7	8	9	
Number of SIF files	140	167	97	404
SIF files total size [GB]	2.71	5.70	3.57	11.98
Number of ASCII files	140	165	97	402
ASCII files total size [GB]	12.40	25.60	16.30	54.30
Number of CSV files*	174	230	150	554
CSV files total size [GB]	2.33	4.58	3.05	9.96

*Comma-separated value files: Files containing the raw data parsed by date.

Table 27. Size and number of data files generated in the project—towing and recovery trucks

	MTDC vehicle			Grand total
	10	11	12	
Number of SIF files	153	131	162	446
SIF files total size [GB]	4.95	6.00	6.09	17.04
Number of ASCII files	139	130	161	430
ASCII files total size [GB]	21.80	27.50	27.30	76.60
Number of CSV files[*]	228	293	241	762
CSV files total size [GB]	6.39	8.07	8.63	23.09

Because of the complexity of the information collected and the size of the database containing that information, a significant effort was required to prepare the raw data for the analysis. As explained elsewhere in this report, the information was collected using a DAS that saved the information in its proprietary format (i.e., SIE files; SoMat was the manufacturer of the equipment used in the data collection task). These binary files were saved using a data structure format that optimizes the size and accessibility of the information, which was also optimized for wireless downloading of the data. (Note: in Part 1 of the MTDC FOT, the data collected using the DAS was in SIF format, which was changed to a newer SIE format for Part 2 of the MTDC FOT.) The information stored in this proprietary SIE format was exported by means of software developed by ORNL to a flat text (i.e., ASCII) format that is readable by any user.

The software developed by ORNL in the Part 1 MTDC FOT for retrieval of the information collected "over the air" was revised and adapted to the new SoMat data structure to take advantage of the new features introduced by the manufacturer of the data collection equipment. The protocol used to save the information collected by the instrumented vehicles was similar to that used in Part 1 of the MTDC FOT, with minor modifications. Every night (7:00 to 9:00 p.m. for the utility vehicles and 1:00 to 3:00 a.m. for the towing and recovery trucks) the ORNL data retrieval software automatically contacted each vehicle and retrieved the SIE file with the information collected during that particular (or previous) day. The SIE file was then translated into an easily readable format as explained above, and the information was parsed into the 70+ channels collected, and saved to files that stored one day's worth of data collection data. These files were named with the calendar date on which the data was collected (e.g., 20111113 for information collected on November 13, 2011) plus a numerical value that identified the test vehicle (7 to 12), and saved as a CSV file, a type of file readable by most text readers, spreadsheet programs, and data analysis software . The data was backed up daily to an external drive connected to the computer running the wireless data-retrieval software and to ORNL servers located off-site.

Concurrent with the formatting of the information from binary to ASCII/CSV, the ORNL-developed software checked the validity of the data provided by the 70+ channels. Sometimes there were cases in which the DAS had problems storing the data ("eDAQ invalid data") or the onboard sensors did not provide information because of, for example, a malfunction of the sensor ("sensor invalid data"). Each one of the collected channels of information had a numeric code that identified these types of problems, and those codes were stored in the file for that particular channel and record. The data cleansing software read this information, generated statistics, and automatically emailed them every morning to the ORNL researchers in charge of the data collection effort. This information allowed the researchers to determine when a certain sensor was systematically failing or when the failures were just glitches that occurred sporadically. In the first case, troubleshooting and repair/replacement of the particular sensor were accomplished as soon as was feasible.

Errors attributed to the onboard GPS device, out-of-range errors, and other similar errors were also identified, and indications of their occurrence were added to the summary reports. Any record that had any kind of error for any channel was marked with a code that allowed for the identification of those errors, and this information was added to the corresponding calendar date file as a new field.

The data-checking and formatting software, however, did not provide any alerts if the data was within a certain logical range. This, as discussed later in this report, produced instances in which the data collected appeared to be normal to the software but actually posed some problems. In particular, this was the case with the weight data, for which the information was within a reasonable range for the type of vehicle for which the data was collected, but presented anomalies (randomness, fluctuations, and drifting) that were identified only once the data was analyzed. (Note: The Data Quicklook Tool was created in response to errors detected neither by the sensor itself nor the DAS. It allowed for pre-analysis but was not available at the start of the project.)

5.1.1 Spatial Information

As was the case with the Part 1 MTDC FOT, in Part 2, the spatial location of the participating vehicles (i.e., latitude, longitude, and altitude) provided by the onboard GPS was collected every 0.2 s. Software developed by ORNL post-processed the information collected using the GPS data to determine the road classification (e.g., freeway) and identification (e.g., I-40) on which the vehicle was traveling, whether it was traveling inside or outside an urban area, and the state in which the truck was located.

5.1.2 Vehicle Weight Information

Vehicle load, a key variable in any study involving the FE, was collected for the towing and recovery vehicles. Because the weight of the utility vehicles was almost constant (i.e., it varied only slightly if additional tools were carried), load information for this vocation was not collected.

Air-Weigh devices were mounted on the three participating towing and recovery vehicles and provided instantaneous weight measurements at the steer and drive axles, which were saved as two of the 70+ data channels of the DAS. One of the vehicles, vehicle 12, had air suspension; an Air-Weigh device and sensors similar to those used in the HTDC and Part 1 of the MTDC projects was used in this case[19]. The other two vehicles (MTDC vehicles 10 and 11) had spring suspensions; therefore, a different type of Air-Weigh device, one that relies on strain gages, was used. In both cases, the Air-Weigh devices posted the instantaneous axle loads to the vehicle data bus, from which it was read by the DAS.

The Air-Weigh devices were calibrated using the procedure specified by the manufacturer (i.e., empty and loaded vehicle) using portable scales provided and operated by the THP. The calibration was conducted at the FCWS garage.

5.1.3 Additional Information

The data collected was post-processed to generate additional information, which was added to the database established in this project. This included roadway slope (in percent), which was computed using the altitude data gathered with the help of the GPS device and filtered to smooth out local fluctuations due to GPS errors; and filtered vehicle speed, which was later used to determine acceleration, deceleration,

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[19] This type of Air-Weigh device uses inputs from the vehicle air-suspension system. Only the drive axle weight is measured; the steer axle weight is computed by the Air-Weigh device.

and constant speed intervals[20]. The filter used was a sliding exponential smoothing filter that considered the median of 11 observations before and 11 observations after the current point.

5.1.4 Information Indexing

The same procedure used in the Part 1 MTDC FOT (and in the HTDC project) was used to index the information collected. This indexing of the data was done in order to efficiently find and retrieve specific information from the large database of information collected (130 GB for Part 2 of the MTDC FOT). A database of pointers was created to allow for quick retrieval of data records that comply with possibly multiple search criteria specified by the analyst. The procedure is described in detail in Section 4.1.4.

The information collected in Part 2 of the MTDC FOT was added to the existing HTDC/Part 1 MTDC FOT database and made available to the user through a menu choice that allows selecting information about Class-8 trucks, mid-size combination trucks, transit buses, utility vehicles, or towing and recovery trucks (see Figure 93). Figure 94and Figure 95 show screen captures of the data selection criteria that are part of the prototype DCGenT for the utility vehicles and towing and recovery trucks, respectively. Those criteria include the following:

1. time of day (peak and off-peak periods),
2. precipitation (indicated by wiper status),
3. roadway type (freeways or surface streets),
4. spatial location (urban or rural areas),
5. congestion level based on vehicle speed and road type,
6. topography (different types of terrain, from up slope to flat to down slope),
7. specific vehicle (one or more of the three instrumented utility vehicles, or one or more of the three instrumented towing and recovery trucks),
8. vehicle dynamic condition (e.g., truck stationary, truck accelerating), and
9. vehicle weight (in four levels: empty, light load, medium load, and heavy load) for the towing and recovery trucks.

Figure 93. Vehicle class and vocation selection menu.

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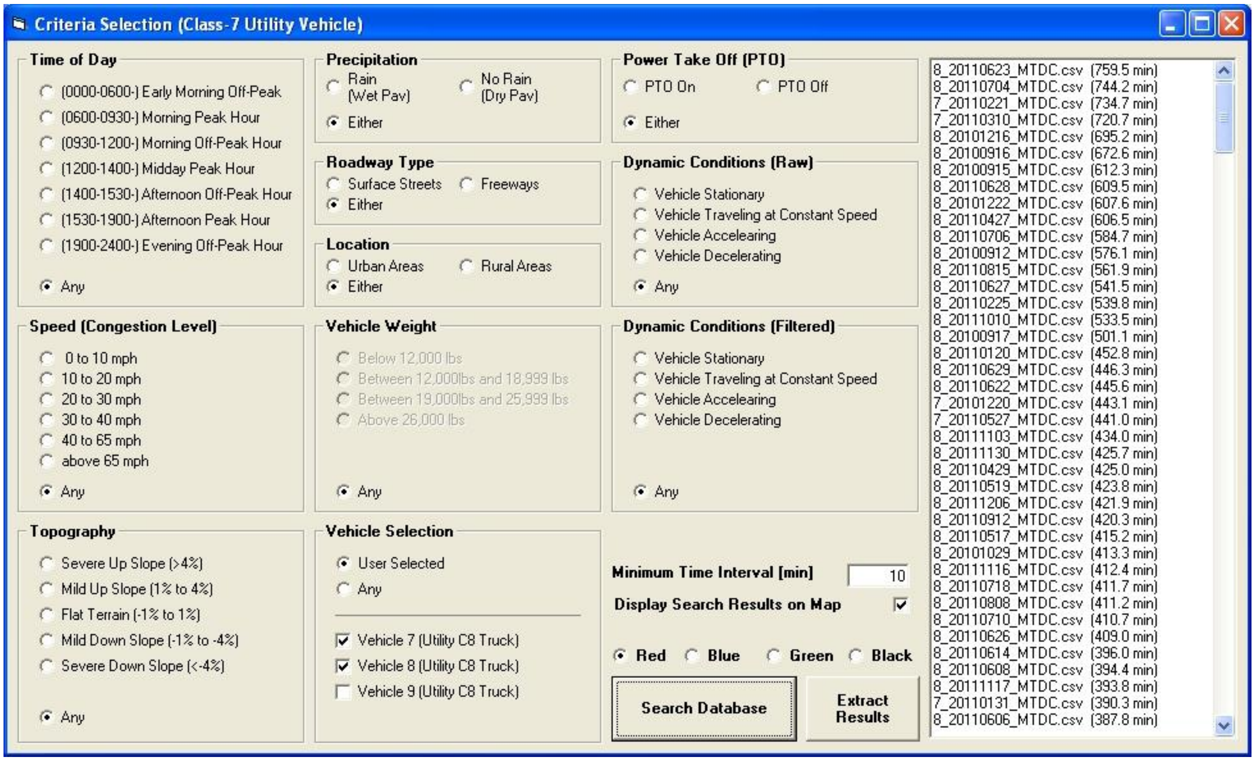
[20] Filtering was needed because of the inherent fluctuations in the data which, if not filtered, would have introduced errors into the data analyses.


Criteria Selection (Class-7 Utility Vehicle)

Time of Day
○ (0000-0600-) Early Morning Off-Peak
○ (0600-0930-) Morning Peak Hour
○ (0930-1200-) Morning Off-Peak Hour
○ (1200-1400-) Midday Peak Hour
○ (1400-1530-) Afternoon Off-Peak Hour
○ (1530-1900-) Afternoon Peak Hour
○ (1900-2400-) Evening Off-Peak Hour
● Any

Precipitation
○ Rain (Wet Pav) ○ No Rain (Dry Pav)
● Either

Roadway Type
○ Surface Streets ○ Freeways
● Either

Location
○ Urban Areas ○ Rural Areas
● Either

Power Take Off (PTO)
○ PTO On ○ PTO Off
● Either

Dynamic Conditions (Raw)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

Speed (Congestion Level)
○ 0 to 10 mph
○ 10 to 20 mph
○ 20 to 30 mph
○ 30 to 40 mph
○ 40 to 65 mph
○ above 65 mph
● Any

Vehicle Weight
○ Below 12,000 lbs
○ Between 12,000lbs and 18,999 lbs
○ Between 19,000lbs and 25,999 lbs
○ Above 26,000 lbs
● Any

Dynamic Conditions (Filtered)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

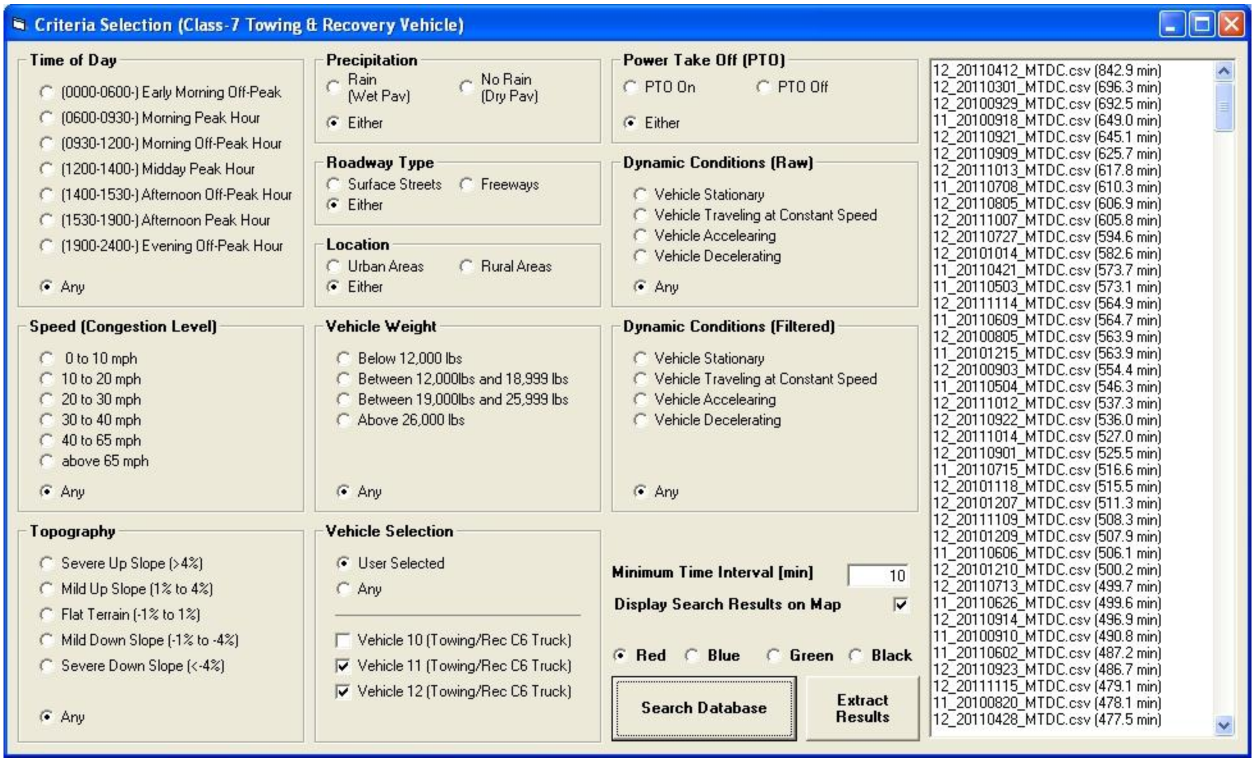
Topography
○ Severe Up Slope (>4%)
○ Mild Up Slope (1% to 4%)
○ Flat Terrain (-1% to 1%)
○ Mild Down Slope (-1% to -4%)
○ Severe Down Slope (<-4%)
● Any

Vehicle Selection
● User Selected
○ Any
☑ Vehicle 7 (Utility C8 Truck)
☑ Vehicle 8 (Utility C8 Truck)
☐ Vehicle 9 (Utility C8 Truck)

Minimum Time Interval (min) 10
Display Search Results on Map ☑
● Red ○ Blue ○ Green ○ Black

8_20110623_MTDC.csv (759.5 min)
8_20110704_MTDC.csv (744.2 min)
7_20110221_MTDC.csv (734.7 min)
7_20110310_MTDC.csv (720.7 min)
8_20101216_MTDC.csv (695.2 min)
8_20100916_MTDC.csv (672.6 min)
8_20100915_MTDC.csv (612.3 min)
8_20110628_MTDC.csv (609.5 min)
8_20101222_MTDC.csv (607.6 min)
8_20110427_MTDC.csv (606.5 min)
8_20110706_MTDC.csv (584.7 min)
8_20100912_MTDC.csv (576.1 min)
8_20110815_MTDC.csv (561.9 min)
8_20110627_MTDC.csv (541.5 min)
8_20110225_MTDC.csv (539.8 min)
8_20111010_MTDC.csv (533.5 min)
8_20100917_MTDC.csv (501.1 min)
8_20110120_MTDC.csv (452.8 min)
8_20110629_MTDC.csv (446.3 min)
8_20110622_MTDC.csv (445.6 min)
7_20101220_MTDC.csv (443.1 min)
7_20110527_MTDC.csv (441.0 min)
8_20111103_MTDC.csv (434.0 min)
8_20111130_MTDC.csv (425.7 min)
8_20110429_MTDC.csv (425.0 min)
8_20110519_MTDC.csv (423.8 min)
8_20111206_MTDC.csv (421.9 min)
8_20110912_MTDC.csv (420.3 min)
8_20110517_MTDC.csv (415.2 min)
8_20101029_MTDC.csv (413.3 min)
8_20111116_MTDC.csv (412.4 min)
8_20110718_MTDC.csv (411.7 min)
8_20110808_MTDC.csv (411.2 min)
8_20110710_MTDC.csv (410.7 min)
8_20110626_MTDC.csv (409.0 min)
8_20110614_MTDC.csv (396.0 min)
8_20110608_MTDC.csv (394.4 min)
8_20111117_MTDC.csv (393.8 min)
7_20110131_MTDC.csv (390.3 min)
8_20110606_MTDC.csv (387.8 min)

Figure 94. Criteria selection—utility vehicles.


Criteria Selection (Class-7 Towing & Recovery Vehicle)

Time of Day
○ (0000-0600-) Early Morning Off-Peak
○ (0600-0930-) Morning Peak Hour
○ (0930-1200-) Morning Off-Peak Hour
○ (1200-1400-) Midday Peak Hour
○ (1400-1530-) Afternoon Off-Peak Hour
○ (1530-1900-) Afternoon Peak Hour
○ (1900-2400-) Evening Off-Peak Hour
● Any

Precipitation
○ Rain (Wet Pav) ○ No Rain (Dry Pav)
● Either

Roadway Type
○ Surface Streets ○ Freeways
● Either

Location
○ Urban Areas ○ Rural Areas
● Either

Power Take Off (PTO)
○ PTO On ○ PTO Off
● Either

Dynamic Conditions (Raw)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

Speed (Congestion Level)
○ 0 to 10 mph
○ 10 to 20 mph
○ 20 to 30 mph
○ 30 to 40 mph
○ 40 to 65 mph
○ above 65 mph
● Any

Vehicle Weight
○ Below 12,000 lbs
○ Between 12,000lbs and 18,999 lbs
○ Between 19,000lbs and 25,999 lbs
○ Above 26,000 lbs
● Any

Dynamic Conditions (Filtered)
○ Vehicle Stationary
○ Vehicle Traveling at Constant Speed
○ Vehicle Accelearing
○ Vehicle Decelerating
● Any

Topography
○ Severe Up Slope (>4%)
○ Mild Up Slope (1% to 4%)
○ Flat Terrain (-1% to 1%)
○ Mild Down Slope (-1% to -4%)
○ Severe Down Slope (<-4%)
● Any

Vehicle Selection
● User Selected
○ Any
☐ Vehicle 10 (Towing/Rec C6 Truck)
☑ Vehicle 11 (Towing/Rec C6 Truck)
☑ Vehicle 12 (Towing/Rec C6 Truck)

Minimum Time Interval (min) 10
Display Search Results on Map ☑
● Red ○ Blue ○ Green ○ Black

12_20110412_MTDC.csv (842.9 min)
12_20110301_MTDC.csv (696.3 min)
12_20100929_MTDC.csv (692.5 min)
11_20100918_MTDC.csv (649.0 min)
12_20110921_MTDC.csv (645.1 min)
12_20110909_MTDC.csv (625.7 min)
12_20111013_MTDC.csv (617.8 min)
11_20110708_MTDC.csv (610.3 min)
12_20110805_MTDC.csv (606.9 min)
12_20111007_MTDC.csv (605.8 min)
12_20110727_MTDC.csv (594.6 min)
12_20101014_MTDC.csv (582.6 min)
11_20110421_MTDC.csv (573.7 min)
11_20110503_MTDC.csv (573.1 min)
12_20111114_MTDC.csv (564.9 min)
11_20110609_MTDC.csv (564.7 min)
12_20100805_MTDC.csv (563.9 min)
11_20101215_MTDC.csv (563.9 min)
12_20100903_MTDC.csv (554.4 min)
11_20110504_MTDC.csv (546.3 min)
12_20111012_MTDC.csv (537.3 min)
12_20110922_MTDC.csv (536.0 min)
12_20111014_MTDC.csv (527.0 min)
12_20110901_MTDC.csv (525.5 min)
11_20110715_MTDC.csv (516.6 min)
12_20101118_MTDC.csv (515.5 min)
12_20101207_MTDC.csv (511.3 min)
12_20111109_MTDC.csv (508.3 min)
12_20101209_MTDC.csv (507.9 min)
11_20110606_MTDC.csv (506.1 min)
12_20101210_MTDC.csv (500.2 min)
12_20110713_MTDC.csv (499.7 min)
11_20110626_MTDC.csv (499.6 min)
12_20110914_MTDC.csv (496.9 min)
11_20100910_MTDC.csv (490.8 min)
11_20110602_MTDC.csv (487.2 min)
12_20110923_MTDC.csv (486.7 min)
12_20111115_MTDC.csv (479.1 min)
11_20100820_MTDC.csv (478.1 min)
12_20110428_MTDC.csv (477.5 min)

Figure 95. Criteria selection—towing and recovery trucks.

The user selects and marks all of the searching criteria of interest and then presses the *Search Database* button. The software finds the list of pointers for the chosen criteria and retrieves from the database all of the records that satisfy these criteria simultaneously (shown on the scrolling text box on the far right of Figure 94 and Figure 95.

5.2 ADDITIONAL DATA CALIBRATION AND ADJUSTMENTS

5.2.1 Vehicle Weight

As discussed briefly in the last section, the load of the utility vehicles was almost constant, with only small variations, and so weigh sensors were not deployed in this case. The three towing and recovery trucks were instrumented with weigh sensors and weigh devices (both provided by Air-Weigh) that processed the data collected by these sensors and posted the information, in the form of axle load, on the vehicle data bus. Two of the vehicles, 10 and 11, had spring suspensions, and the third one (MTDC vehicle 12) had air suspension. The former vehicles were mounted with strain gages and the latter with an air-pressure transducer. The three vehicles were calibrated using the methodology suggested by the manufacturer and with the help of portable CMV scales provided and operated by the THP. The calibration of the Air-Weigh devices was performed on July 28, 2010, at the FCWS garage. The results of the calibration are presented in Table 28. Vehicles 10 and 11 were similar (see Subsection 2.3) and showed similar weights for the empty and loaded conditions, respectively. Vehicle 12 was slightly larger and heavier.

Table 28. Weight ticket information—loaded truck

Vehicle	Load level	Axle	Axle and total weight [lb]		
			At calibration	Shortly after calibration	End of project
10	Empty	Steer	7,100	6,746	Invalid[*]
		Drive	8,000	1,204	Invalid
		Total	15,100	7,950	Invalid
	Loaded	Load	9,600	N/A[**]	N/A
		Steer	7,850	6,840	Invalid
		Drive	17,450	2,478	Invalid
		Total	25,300	9,318	Invalid
11	Empty	Steer	6,700	5,,860	Invalid
		Drive	8,900	99,590	Invalid
		Total	15,600	105,450	Invalid
	Loaded	Load	9,650	N/A	N/A
		Steer	7,500	6,840	Invalid
		Drive	17,750	106,800	Invalid
		Total	25,250	113,640	Invalid
12	Empty	Steer	6,300	6,323	6,601
		Drive	10,450	10,270	10,240
		Total	16,750	16,593	16,841
	Loaded	Load	9,250	N/A	N/A
		Steer	7,200	6,925	6,993
		Drive	18,800	14,400	15,370
		Total	26,000	21,325	22,363

[*] Information outside weight range. [**] Information not available.

Table 28 presents two additional columns. The first of these (labeled "Shortly after Calibration") shows readings posted by the weigh device with information collected from the weigh sensors about 2 months after the manual calibration of the devices was performed. Whereas vehicle 12 shows readings that are close to those obtained under the two-calibration conditions,[21] vehicles 10 and 11 are completely off. In particular, the strain gages measuring the loads for the driver axles showed figures that were unreasonable. This indicated to the researchers that the strain gages had failed sometime in the first or second month of the FOT. It was decided not to replace them since there was a clear indication that they would need to be replaced every few weeks, causing downtime for the towing and recovery vehicles that were participating in the FOT on a gratis arrangement. Data collected toward the end of the test (right column in Table 28) showed that the strain-gage-based systems were completely nonoperational, but the air-pressure sensors were still providing reasonable readings.

When the Part 2 MTDC FOT ended and the information collected was more thoroughly analyzed, it was discovered that even the weight information collected by vehicle 12 presented some anomalies. Specifically, when the vehicle was moving, the axle-weight information collected showed numerous and significantly high spikes that sometimes were ten times larger than the expected reading. However, when the vehicle was in a stationary position, this problem was not observed. The chart at the top of Figure 96 (labeled "Raw Data") shows this data issue by displaying the speed of the vehicle (wbvs: wheel-based vehicle speed) and the vehicle total weight (GVW) divided by 100 as a function of time.

Based on these observations, an algorithm was developed to correct this significant data noise. This algorithm followed these steps:

1. Remove invalid and out-of-range values, including readings of 0 and replace these values with a null (see the second chart from the top in Figure 96).
2. Remove at-speed (wbvs>0) weight readings and replace these values with a null (see second chart from the top in Figure 96).
3. Replace missing data between PTO operations with average weight over that segment between PTO operations (see the third chart from the top in Figure 96).
4. Replace missing data during PTO operations with the average of the weights immediately before and after the missing data (see the third chart from the top in Figure 96).

The incorporation of the PTO signal into the algorithm was based on the fact that significant load changes (loading or offloading a vehicle) require PTO operation. Other, smaller load changes (such as passengers getting on and off) will take place only at stops as well and will therefore be retained in the data (provided the onboard system supplies valid data). To avoid giving undue weight to any particular reading during the load interval in which the terrain slope is unknown, the average of the valid readings collected over this particular load interval was used as a substitute for this missing data. Missing data from the interval when the PTO was operating (i.e., an interval during which the load is changing) was replaced with the average of the previous and following valid data values. An example of the application of this weight-data correction algorithm is presented in Figure 97. With these corrections, the weight data from vehicle 12 could be used in the analysis.

---

[21] The data presented in the table was obtained directly from the information collected by the vehicles. While it is possible to determine when a vehicle was empty, it is not feasible to assess when the vehicle had the same load as the one used in the calibration for the "loaded" condition. Therefore, the figures shown in the table for the loaded condition for the "Shortly after Calibration" period are merely indications and cannot be compared directly with the ones from the "At Calibration" period. However, these figures should be reasonable and should be larger than the ones for the empty condition.

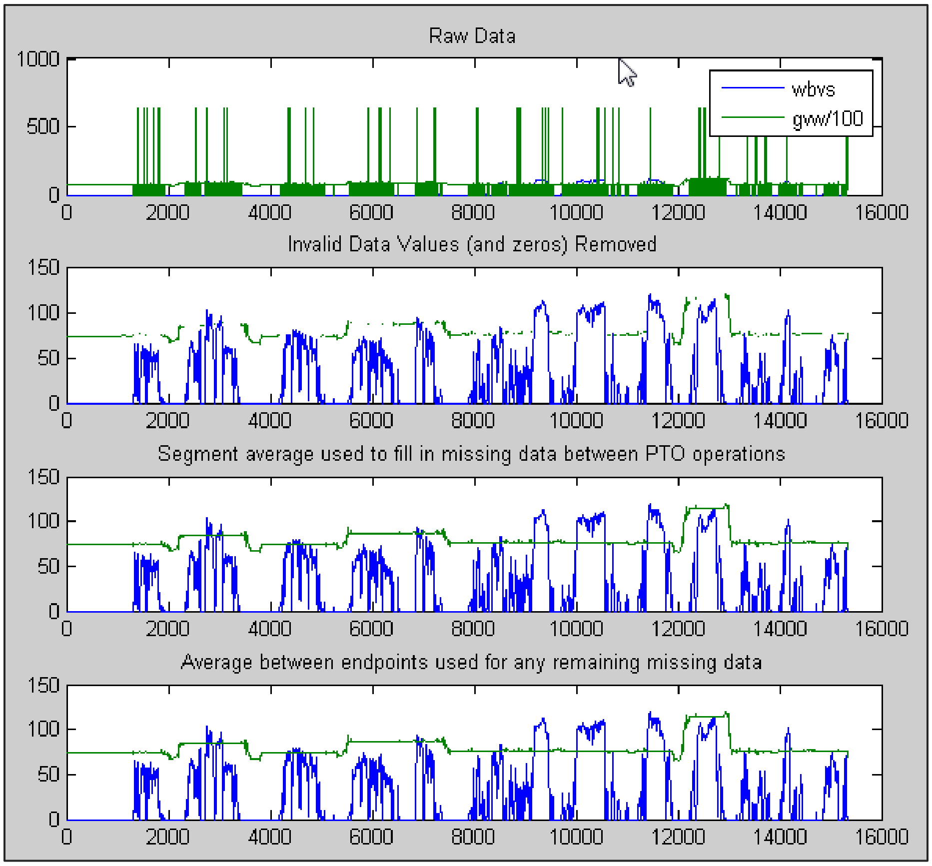


Figure 96. Weight-data cleansing steps.

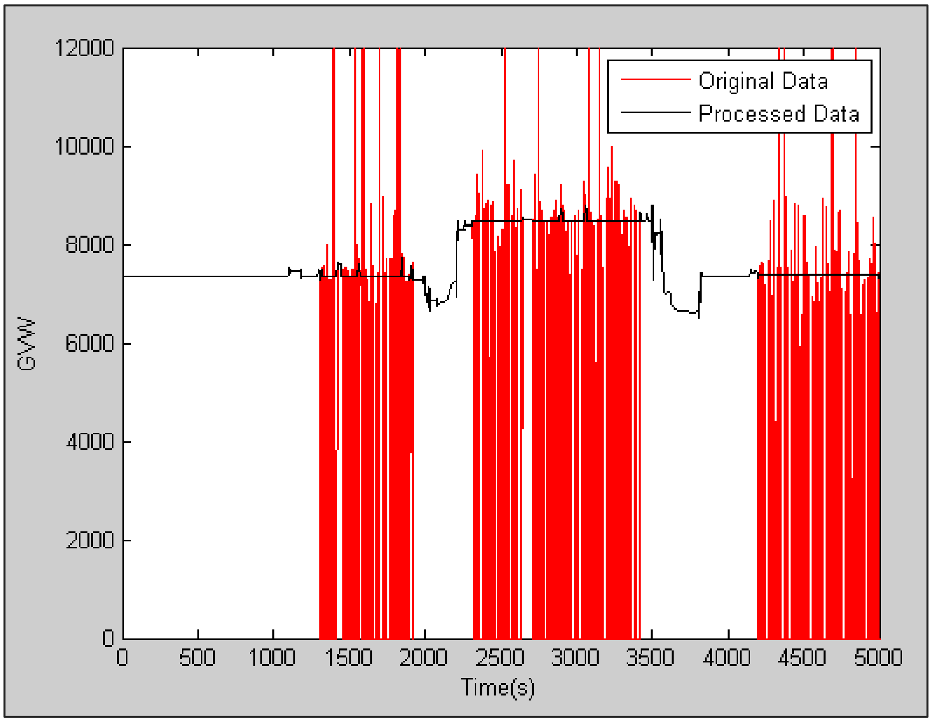


Figure 97. Original and processed weight information (MTDC vehicle 12).

5.2.2 Grade Filtering

Vehicle load and roadway profile (i.e., roadway grade) are two of the most important variables affecting the FE of any vehicle. The GPS data collected in the MTDC and HTDC projects was used to determine roadway grade, and the computed grade was added to the database. Because roads are built as a set of segments with constant slope connected by well-defined vertical and horizontal curves, the grade of the road traveled by a vehicle participating in the projects was computed using the following methodology. From a starting position *S* (see Figure 98) with known altitude *Alt(S)* provided by the onboard GPS device, the speed of the vehicle was integrated over time until the truck had advanced a distance *D* = 100 ft (or slightly over 100 ft). That location was defined as the end position *E*, and was also characterized by a GPS-provided altitude *Alt(E)*. The roadway grade *RG* (in %) was then computed as the difference between the ending and starting altitudes, Δ*Z*, divided by the distance *D* and multiplied by 100. Any point between the start and end location of the roadway segment under consideration was assigned the same grade *RD*. The process was then repeated starting from the end position of the prior segment, which became the new start position. This procedure was conducted for all segments until all of the information collected was processed. This methodology worked very well and provided accurate information regarding roadway grade. Roadway grades generated in this way made it easier to classify the data as belonging to different types of terrain (e.g., flat terrain vs. severe downslope) than would simply using the GPS altitude to compute grade for each record (obtained at a frequency of one data record every 0.2 s). The latter method provided “noisy” grade information and was therefore not used.

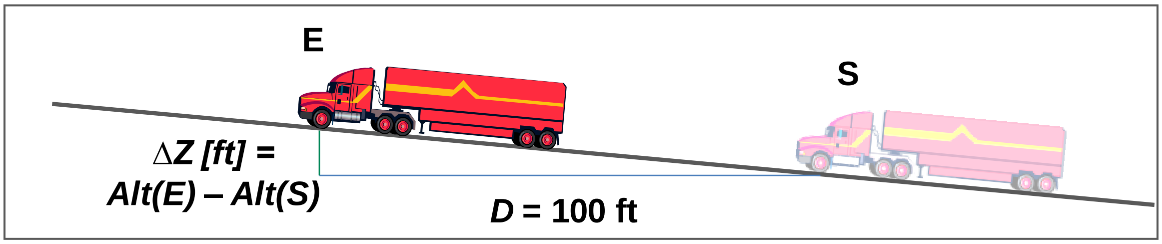


Figure 98. Grade computation using GPS altitude and vehicle data bus information.

Different checking procedures were used to determine the accuracy of this procedure. For example, the database was searched for trips that used the same road from origin to destination and back. The grades computed with the procedure described above were integrated to obtain a roadway profile (altitude vs. distance) for both travel directions. One of the directions was then mathematically rotated 180° and superimposed on the other. No discrepancies should be present when dealing with surface streets (except for a constant bias), and few discrepancies should be seen when using freeways for this comparison (most discrepancies would occur in cases where lanes for the two directions are separated by several feet and therefore lie on natural terrain that is slightly different in terms of slopes). These examples make use of HTDC data, but the procedure is identical to that used for the MTDC data. Figure 99 shows an example for a participating HTDC vehicle traveling on an Interstate freeway in Utah. The two insets in the figure show the points used as starting and ending (east to west) for the first part of the trip and the reverse for the return (i.e., the vehicle traveled the same road going west and returning east). The grades computed using the procedure described were integrated over the distance traveled for both legs of the trip, and the resulting roadway profiles (after some rotation procedures were applied) are presented in Figure 100 (note: for clarity and easier visual comparison, a constant bias of −300 ft was applied to the eastbound profile, May 7, 2007, to separate it from the westbound profile). The figure shows that both profiles are almost identical (as would be expected).

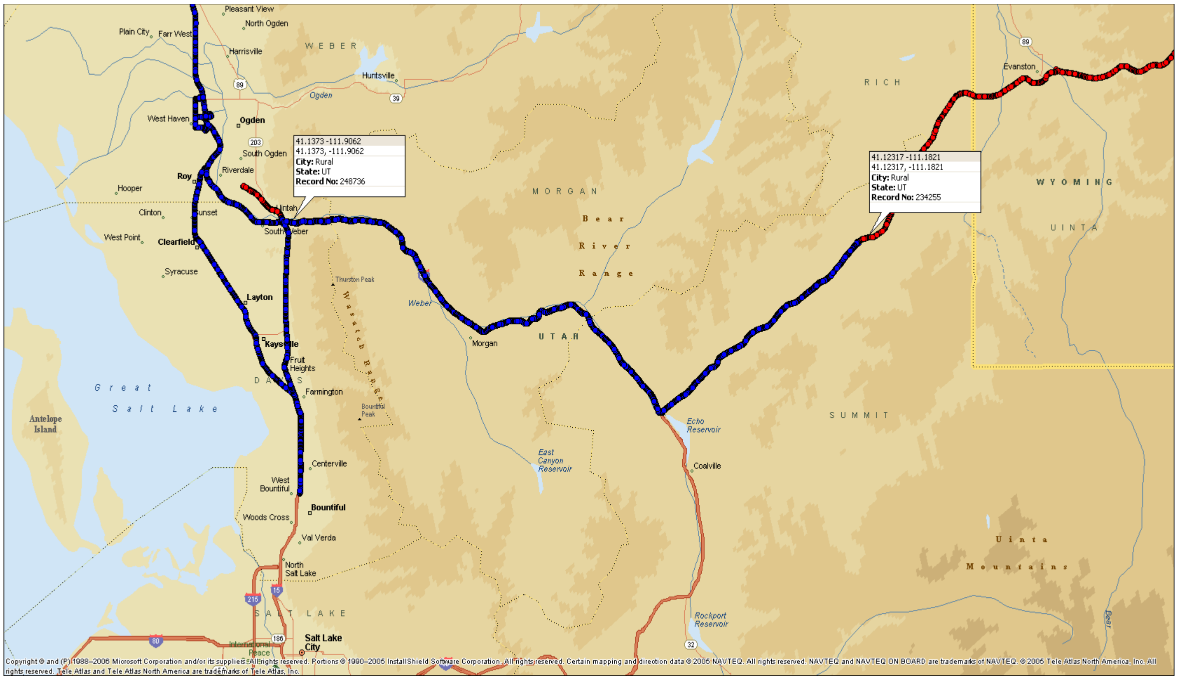


Figure 99. Departure and return trips for HTDC participant vehicle (2007, May 5 and 7).

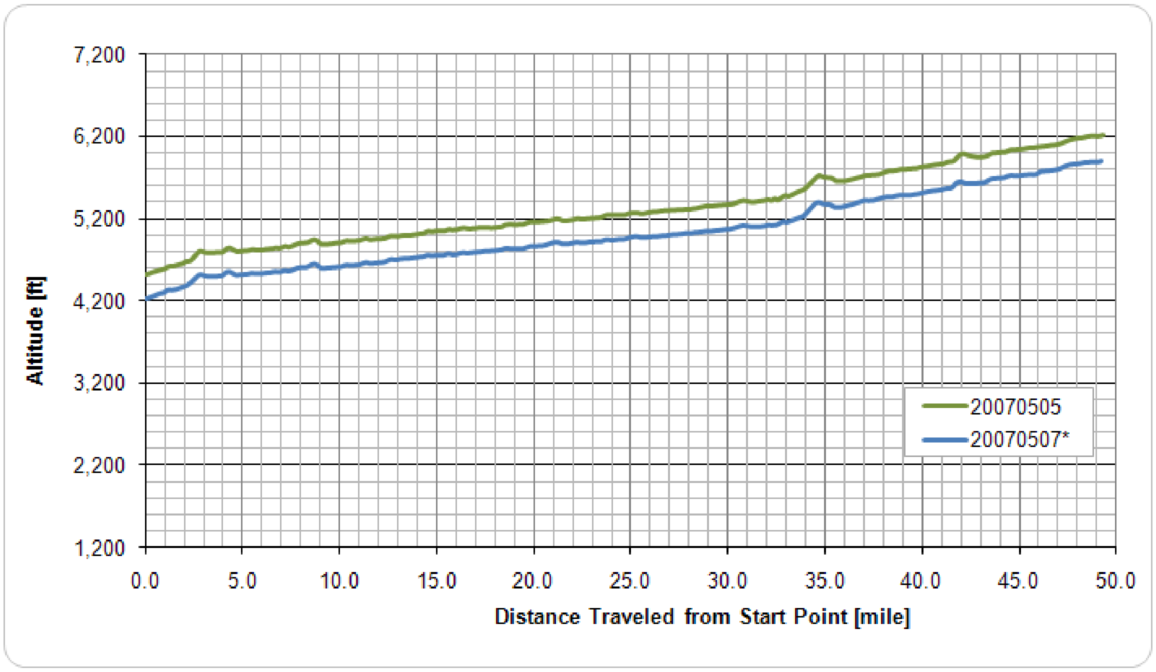


Figure 100. Terrain profiles generated by integrating grade over distance (HTDC, 2007, May 5 westbound and 7 eastbound; *indicates "flipped" diagram).

However, during the data analyses, it was observed that in some cases (i.e., for a particular 100 ft segment) the road grades computed using the procedure described were out of range. For example, in certain cases it was observed that freeway segments showed grades above 8%. This, of course, is an error—interstate freeways are built to a certain standard in terms of grade, and such large grades are never present in mainline freeway segments (they might exist only in on- and off-ramps. Although these observations had a very low probability of occurrence (e.g., they may be observed only in a few instances in a day-long trip, or on about 500 ft of roadway in an 700 mile trip), they were still investigated. In the process, it was observed that when a vehicle was stationary (i.e., was not moving but was idling, so data was collected by the onboard DAS during the idling time), the GPS altitude channel readings were not constant as would be expected, but changed over a period of time, following the pattern of a slow-moving random wave. For example, Figure 101 shows a warehouse in Indiana where one of the participant vehicles was idling for several hours while waiting to pick up a load.

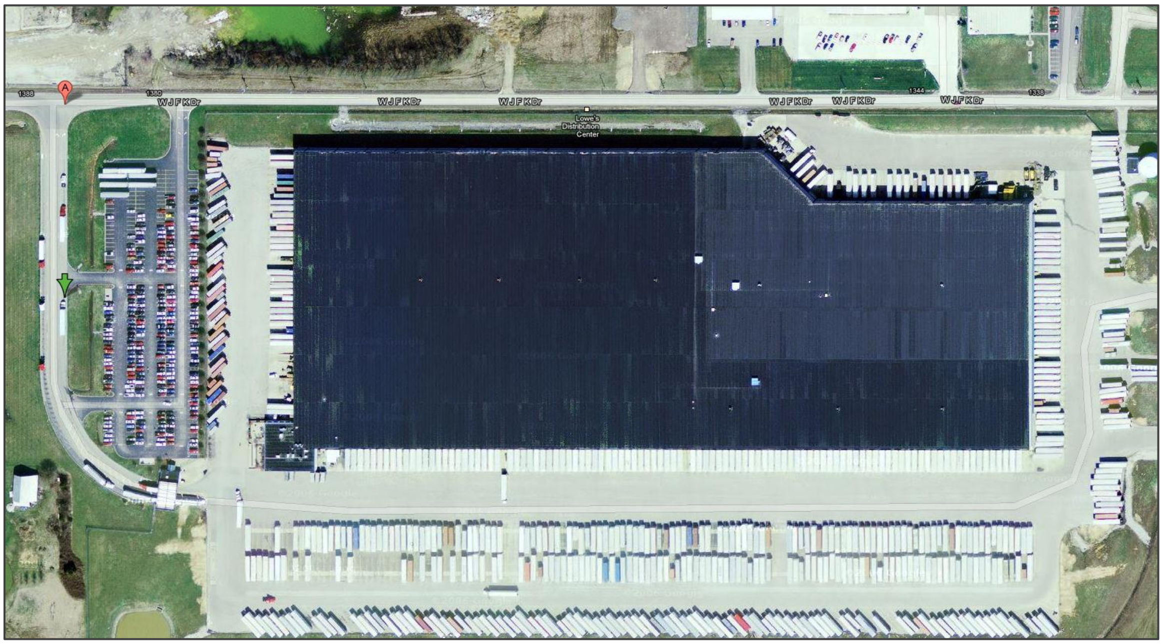


Figure 101. Participant vehicle stationary and idling at a warehouse in North Vernon, IN (July 23, 2007).

Under these conditions (i.e., vehicle stationary), it would be expected that a graph of the vehicle altitude as a function of time would be a flat line. However, this was not the case in this instance, or in any other instance in which any of the 18 participating vehicles were stationary and collecting data. Figure 102 shows both the expected altitude reading (flat, horizontal line since the vehicle is stationary) and the actual readings during a period of 50 min. It can be observed that the registered altitude fluctuates up and down following what appears to be a random low-speed moving wave (i.e., a wave with a frequency of about 7 to 10 min in this particular case). This observed altitude-error wave was responsible for the large grades observed in some cases when the previously described methodology was applied.

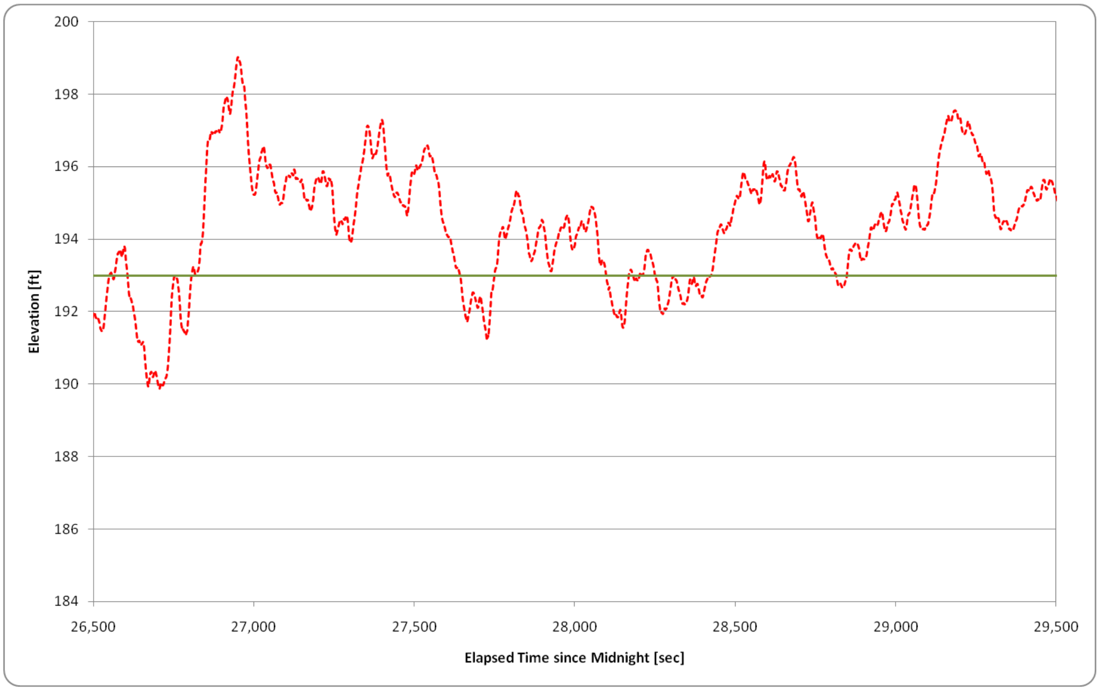


Figure 102. GPS altitude readings (dotted line) vs. time for an HTDC participant vehicle stationary and idling at a warehouse in North Vernon, IN (July 23, 2007).

Consider, for example, Figure 103, which shows altitude readings for a 1 s interval (six readings, dotted line). Although the theorized error-wave is moving, it is doing so at such a slow pace that there are no observable differences in altitude at the beginning and end of the interval. However, if a longer interval is considered, such as a 1 min interval shown in Figure 104, then there could be noticeable differences in altitude between the start and end of that interval.

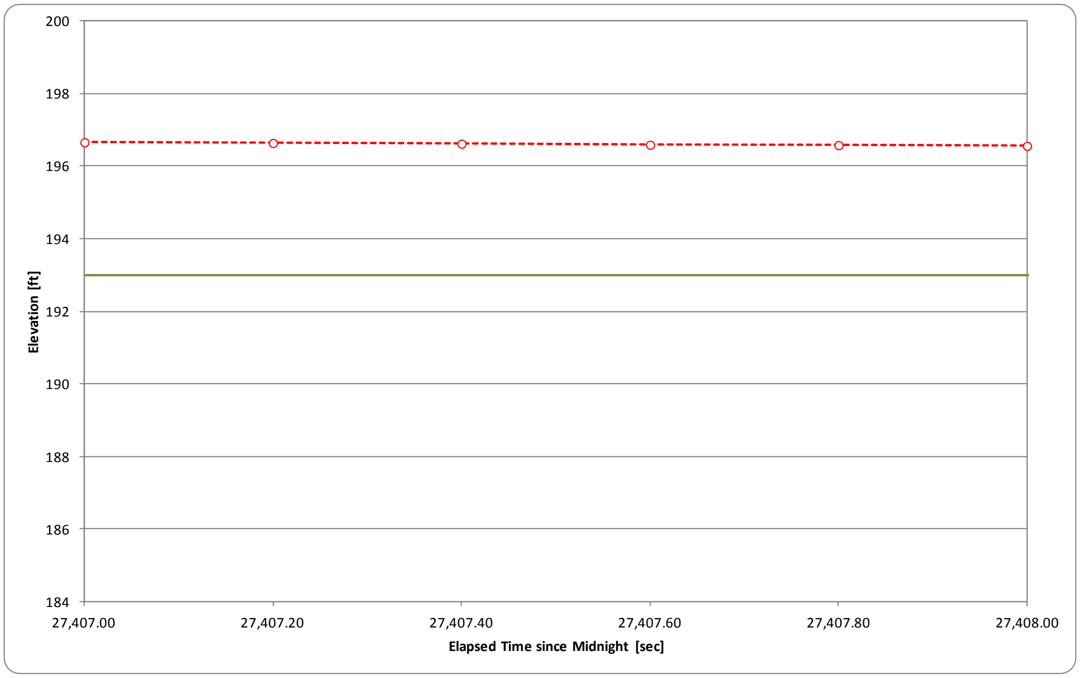


Figure 103. GPS altitude readings (dotted line) vs. time—1 s interval.

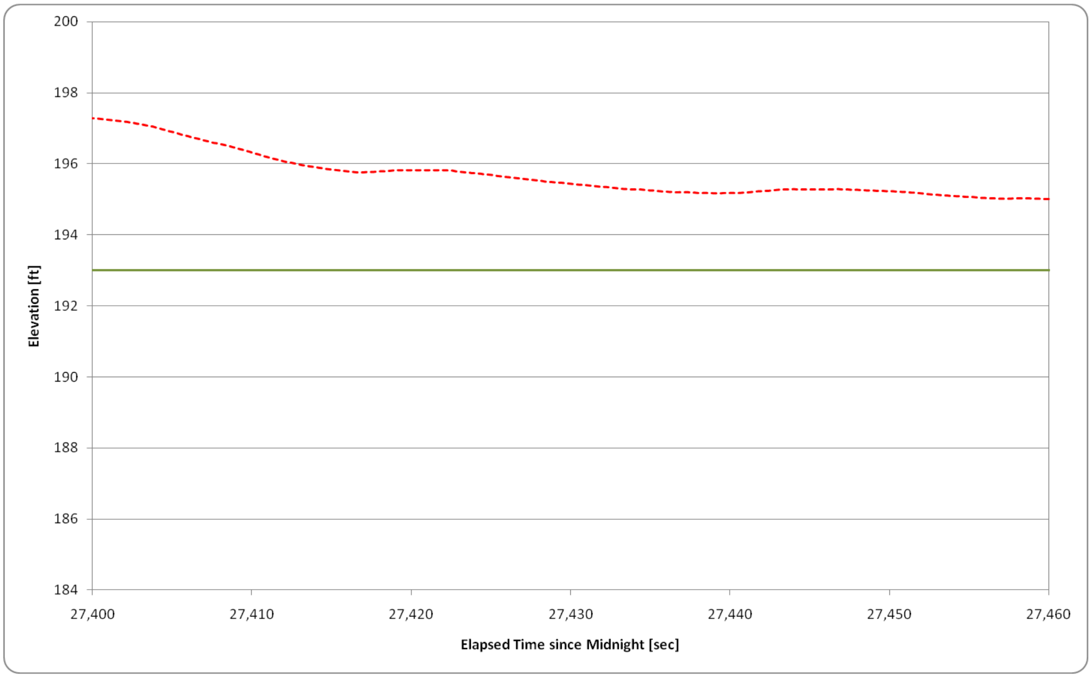


Figure 104. GPS altitude readings (dotted line) vs. time—60 s interval.

The consequence is that if a vehicle takes a long time to travel the 100 ft segment used in the methodology to compute the roadway grade (e.g., a vehicle is coming to a stop due to congestion or any other reason), then the altitudes registered at the beginning and at the end of that segment could be significantly different by virtue of the altitude error. Consider once more Figure 102. If a vehicle were to enter a segment at time 26,700 s and exit that segment 3.5 min later (e.g., because of congestion that reduced speed to 0.5 mph), then the computed grade for that segment would have been 9%, which is erroneous.

An algorithm was developed that determined those segments in which the vehicle was traveling at very low speed (i.e., segments for which it took an extraordinary amount of time to traverse the 100 ft distance[22]). In those cases, the grade was corrected by considering an average of the previous and following segments for the HTDC and Part 1 and Part 2 MTDC databases.

5.3 GENERAL STATISTICS

The data analysis focus for the Part 2 MTDC FOT was on the FE of the utility vehicles and towing and recovery trucks during general operation, operation when using additional equipment (i.e., PTO equipment), and the latter under different payload conditions. The analysis presented here starts with some general statistics that summarize the operation of the two vocations that participated in the Part 2 MTDC FOT. An analysis of the FE of these vehicles follows for cases in which the PTO equipment was used, and with the payload dimension added later in this chapter for the towing and recovery trucks. All of the four vocations participating in the Part 1 and Part 2MTDC FOTs had one operation characteristic in common; all of them made frequent stops during their business hours. An investigation of the distribution of the frequency and duration of these stops, useful for modelers, is also presented at the end of this section.

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[22] At highway speed, a vehicle will traverse a 100 ft segment in just over a second.

5.3.1 General Operations Statistics

In the almost 16-month data collection period, the six vehicles participating in the Part 2 MTDC FOT logged almost 90,000 miles (18,000 for the utility vehicles and 70,000 for the towing and recovery trucks) and consumed over 13,000 gal of fuel (5,000 for the utility vehicles and 8,000 for the towing and recovery trucks) while conducting business in the East Tennessee area and surrounding states. Figure 50 to Figure 52 show the area of operation of the three utility vehicles while Figure 105 to Figure 110 present the superimposed routes for the three towing and recovery vehicles during the 16-month data collection period.

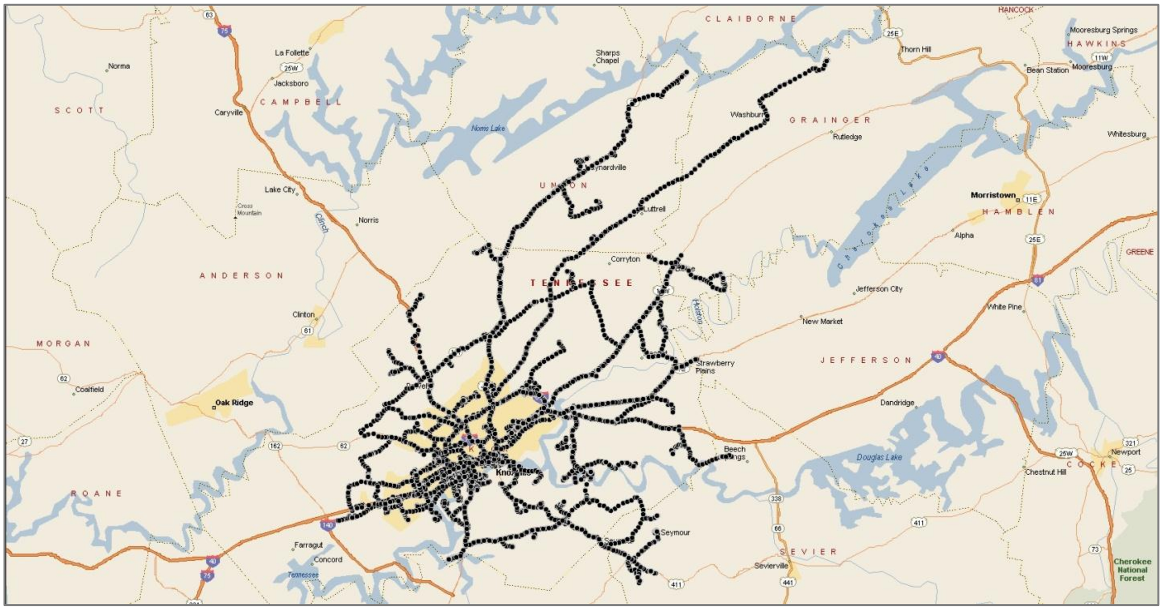

Figure 105. Utility vehicle 1 (MTDC vehicle 7) coverage area.

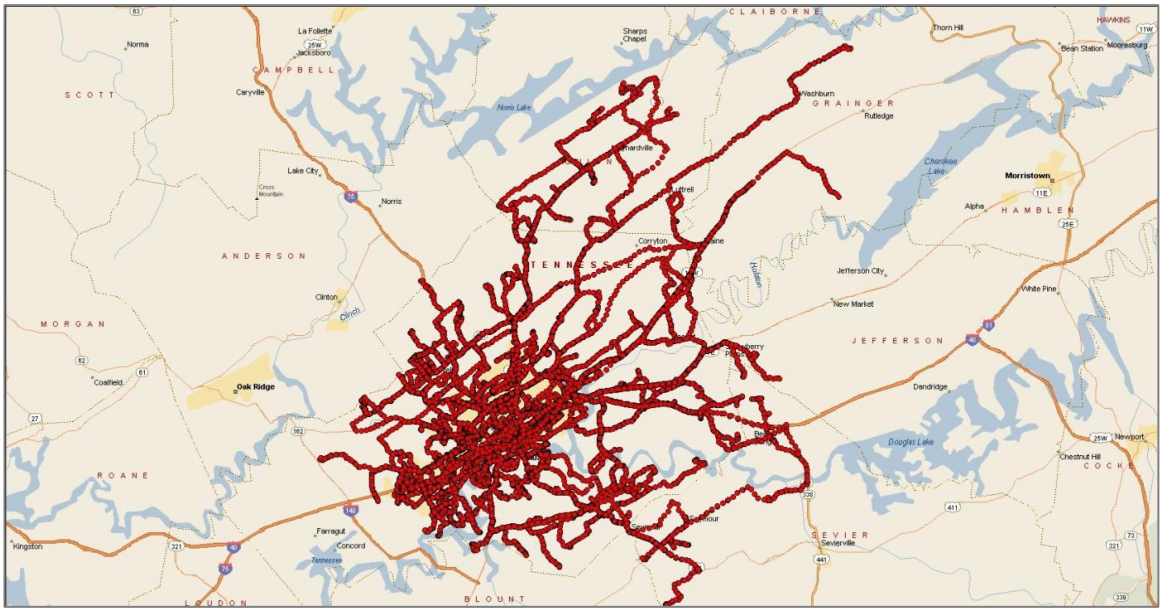

Figure 106. Utility vehicle 2 (MTDC vehicle 8) coverage area.

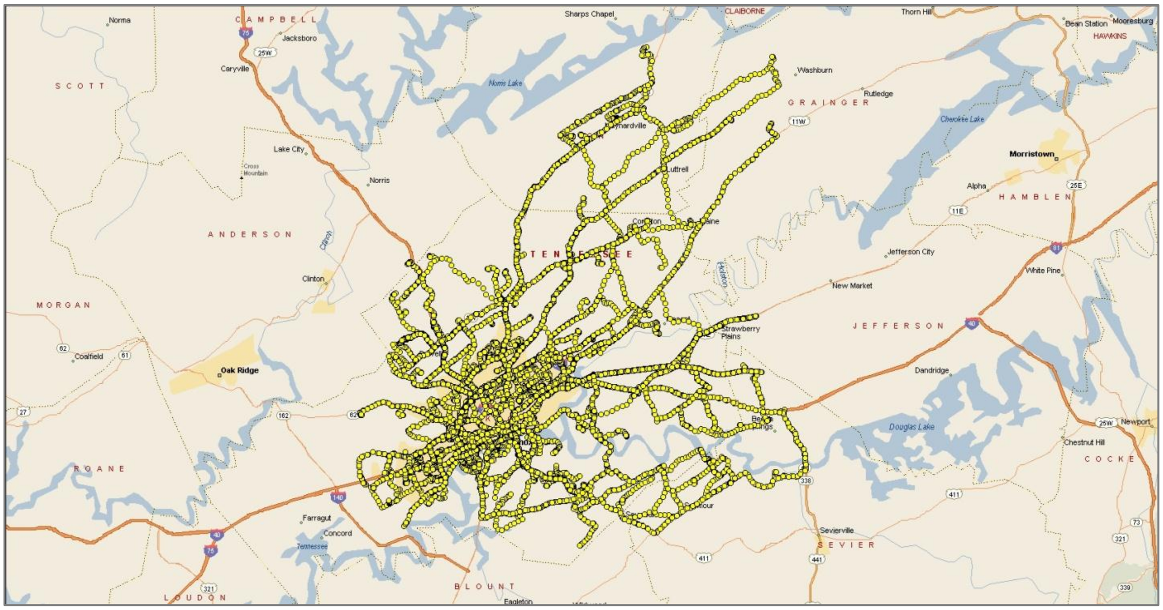

Figure 107. Utility vehicle 3 (MTDC vehicle 9) coverage area.

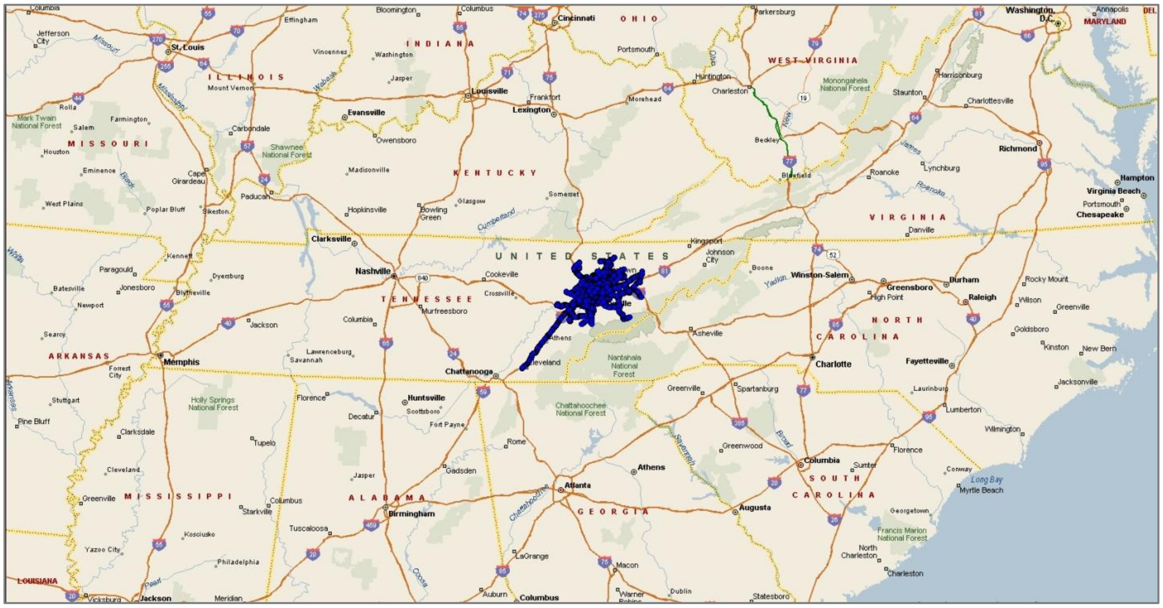

Figure 108. Towing and recovery truck 1 (MTDC vehicle 10) coverage area.

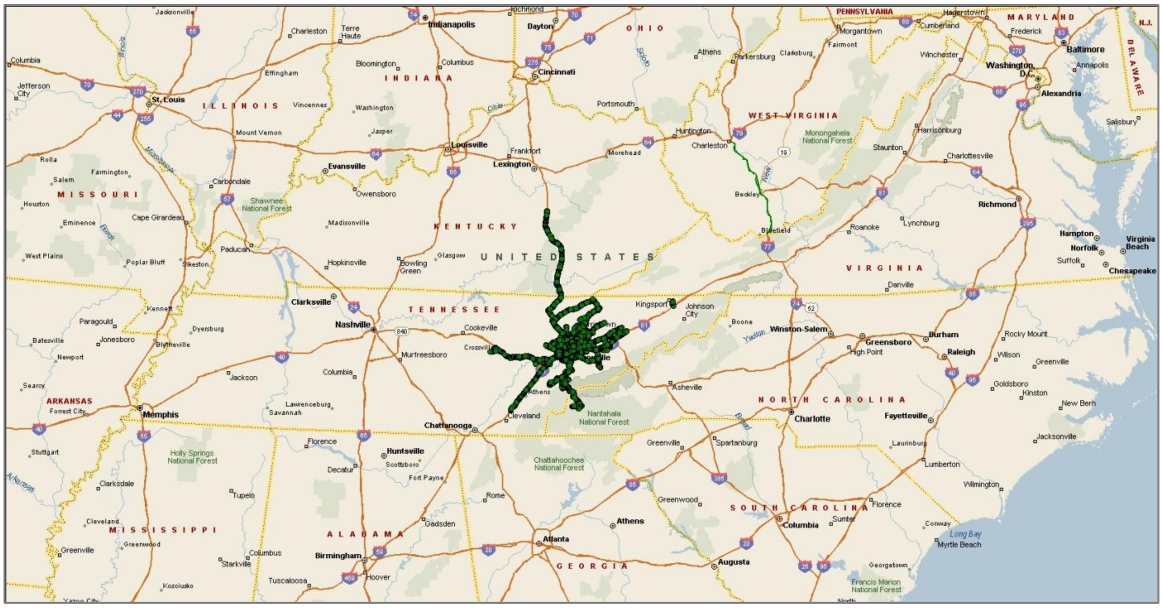

Figure 109. Towing and recovery truck 2 (MTDC vehicle 11) coverage area.

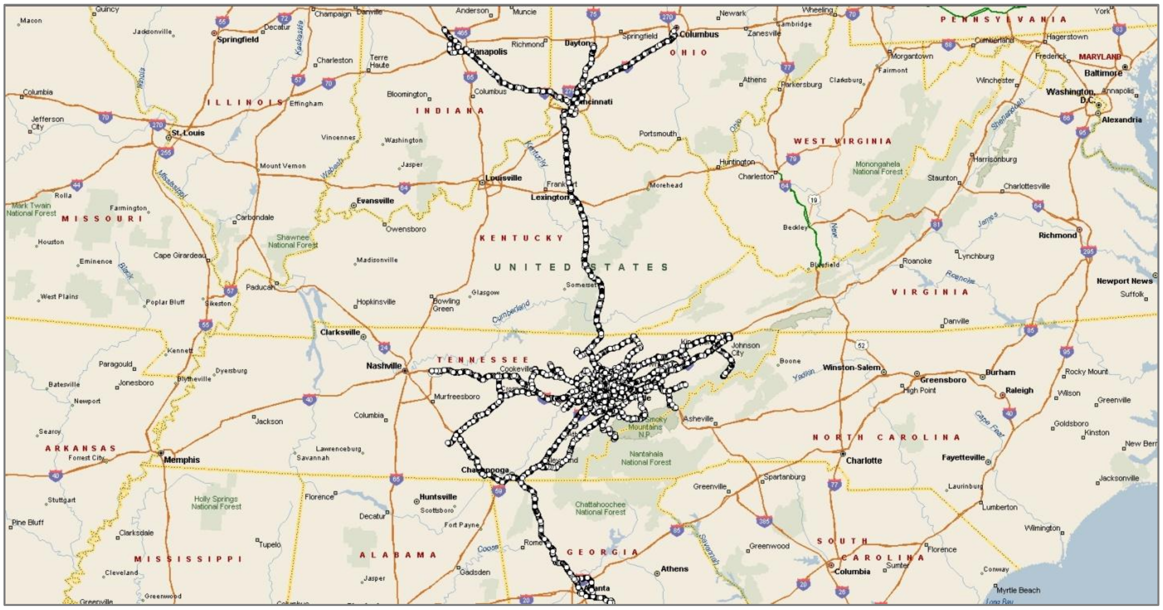

Figure 110. Towing and recovery truck 3 (MTDC vehicle 12) coverage area.

Table 29 and Table 30 show general operational statistics for each of the three participating utility vehicles and the three towing and recovery trucks, respectively. The tables also include information regarding the FEs for the entire data collection period for each of the six vehicles, as well as their overall FE. These calculations were made using fuel consumption information obtained from the vehicles’ data buses (right row in Table 29 and Table 30) and include the fuel consumed when the vehicle was moving or idling. Overall, the Part 1 and Part 2 MTDC FOTs logged more than 190,000 miles of real-world operational data for the four vocations that participated in the project, resulting in a database of more than 210 million records. For the entire program (HTDC and MTDC combined), 870,000 miles were logged, resulting in a database of 640 million records collected at a frequency of one record every 0.2 s.

Table 29. General statistics for the utility vehicles

	MTDC vehicle			Grand total
	7	8	9	
Distance traveled[*] [miles]	4,242	8,345	5,541	18,127
Total time [h]	499	1,023	669	2,191
Average speed [mph]	8.5	8.2	8.3	8.3
Average moving speed [mph]	28.6	30.6	29.1	29.7
Total fuel [gal]	1,551	1,962	1,537	5,051
Overall fuel efficiency[**] [mpg]	2.734	4.252	3.605	3.589

[*] Computed with vehicle databus information (integration of vehicle speed over time). [**] Computed with vehicle databus information on fuel consumption, and integration of vehicle speed over time.

Table 30. General statistics for the towing and recovery trucks

	MTDC vehicle			Grand total
	10	11	12	
Distance traveled[*] [miles]	19,041	23,891	27,019	69,950
Total time [h]	910	1,025	1,100	3,036
Average speed [mph]	20.9	23.3	24.6	23.0
Average moving speed [mph]	37.7	36.9	41.7	38.9
Total fuel [gal]	2,450	2,631	3,049	8,130
Overall fuel efficiency[**] [mpg]	7.771	9.080	8.863	8.604

[*] Computed with vehicle databus information (integration of vehicle speed over time). [**] Computed with vehicle databus information on fuel consumption, and integration of vehicle speed over time.

The information collected during the Part 2 MTDC FOT was used to generate distributions of idling time and idling fuel consumed as a percentage of total time and total fuel consumed, respectively. As was the case for the Part 1 MTDC and HTDC FOTs, seven intervals of time were considered, ranging from 0–5 min (i.e., the vehicle was idling—vehicle static and engine running—for less than 5 min) to more than 4 h. In general, the short intervals correspond to idling due to traffic conditions such as congestion delays and to traffic lights, and the largest one is attributable to garage idling due to maintenance or, for the utility vehicles, idling while conducting electric line maintenance and repairs. Table 31 and Table 32 present idling information for the utility vehicles and the towing and recovery trucks, respectively.

In the case of the utility vehicles (Table 31), the largest proportion of idling time (38%) and fuel consumed (40%) while idling corresponded to idling intervals lasting between 15 and 60 min. This was followed by the 60 to 120 min interval (representing 24% of the idling time and 23% of fuel consumption while idling), and the 2 to 3 h interval, all corresponding to the vehicle parked and idling (to facilitate PTO operation) while maintaining and repairing electric power lines. Delays at traffic lights (0–5 min interval) ranked fourth in terms of idling time and idling fuel consumption, 9% and 8%, respectively.

For the towing and recovery trucks, the largest percentage of idling time and fuel consumed while idling (40% and 41%, respectively), corresponded to the 5 to 15 min interval (see Table 32). The 15–60 min interval ranked third with 25% of the total idling time and 22% of the idling fuel consumed. These two intervals (i.e., 5–15 min and 15–60 min) correspond mostly to the loading and unloading of the vehicles to be towed. Delays at traffic lights accounted for the second-largest percentages of time and fuel spent while idling (31% for both measures). Time spent idling for more than 2 h was negligible in the case of the towing and recovery trucks.

Table 31. Distributions of time spent and fuel consumed while idling (utility vehicles)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	110.4	8.7	5.0	110.0	7.8	2.2
5–15	97.6	7.7	4.5	106.9	7.5	2.1
15–60	488.9	38.4	22.3	560.8	39.6	11.1
60–120	300.4	23.6	13.7	327.8	23.1	6.5
120–180	154.4	12.1	7.0	166.1	11.7	3.3
180–240	43.8	3.4	2.0	51.2	3.6	1.0
240+	78.5	6.2	3.6	94.3	6.7	1.9
TOTAL	**1,274**	**100**	**58.1**	**1,417**	**100**	**28.1**

Table 32. Distributions of time spent and fuel consumed while idling (towing and recovery trucks)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	374.6	30.8	12.3	294.5	31.4	3.6
5–15	482.1	39.7	15.9	380.9	40.6	4.7
15–60	298.4	24.6	9.8	209.0	22.3	2.6
60–120	54.9	4.5	1.8	47.5	5.1	0.6
120–180	5.2	0.4	0.2	5.3	0.6	0.1
180–240	0.0	0.0	0.0	0.0	0.0	0.0
240+	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**1,215**	**100**	**40.0**	**937**	**100**	**11.5**

5.3.2 Vehicle Fuel Efficiency

The overall as well as moving FE of the six vehicles participating in the Part 2MTDC FOT was computed using the information collected in the project. The overall FEs—that is, the FEs computed when taking into consideration idling times as well as the moving FEs (i.e., fuel consumed only when the vehicle was moving)—are presented in Table 33 and Table 34 for the three utility vehicles and three towing and recovery trucks, respectively. The percentage differences between overall and moving FEs for each vehicle are also shown in the tables. Notice that for the utility vehicles, the percentage difference between overall and moving FEs is much higher (about three times higher) than for the towing and recovery trucks. Some of this difference can be attributed to differences between vehicle types (e.g., transmission type, age), but most is due to their idling periods. Although the total miles traveled during the length of the project is about four times higher (i.e., a 400% difference) for the towing and recovery trucks than for the utility vehicles, the former consumed only 50% more fuel than the latter while idling (see Table 31 and Table 32).

Even within each vocation, slightly different vehicles, drivers, and operations resulted in FEs that sometimes were significantly different. Consider the number 8 and 9 utility vehicles; they were the same make, had engines of similar size (although from different manufacturers), and had the same type of transmission (automatic). Vehicle 8 (which was a 2010 model vs. 2004 for vehicle 9) showed better overall and moving FEs, with an advantage of more than 10% over vehicle 9. In the case of vehicles 11 and 12, which were built just a year apart (12 was newer than 11) and were the same make, had the same engine size, and had the same type of transmission (automatic), the differences in overall and moving FEs were very small (less than 1% for the latter). Taking into account the limitations of the project in terms of number of participating vehicles and area of operation, it appears that similar vehicles within a given vocation can be characterized with general parameters for FE. More research involving a larger number of vehicles is needed.

Table 33. Overall and moving FEs—utility vehicles

MTDC vehicle	Overall FE [mpg]	Moving FE [mpg]	Percent difference
7	2.734	3.871	41.57
8	4.252	5.699	34.01
9	3.605	5.162	43.18
All vehicles	**3.589**	**4.989**	**39.00**

Table 34. Overall and moving FEs—towing and recovery trucks

MTDC vehicle	Overall FE [mpg]	Moving FE [mpg]	Percent difference
10	7.771	9.087	16.94
11	9.080	10.019	10.34
12	8.863	9.959	12.37
All Vehicles	**8.604**	**9.725**	**13.03**

5.4 WEIGHT ESTIMATION

5.4.1 Weight Data and Weight Correction Model

Weight data gathering devices were deployed on the three towing and recovery trucks. However, as discussed previously, vehicles 10 and 11 developed problems with the weigh sensors (strain gages in both cases, since those vehicles had spring suspensions) early in the FOT and did not collect any useful weigh information.

Vehicle 12, on the other hand, had air suspension and was instrumented with a different Air-Weigh system from that of the other two vehicles. This vehicle collected steer-axle and drive-axle weight during most of the time it participated in the Part 2 MTDC FOT. (Note: during certain periods of time during the FOT, the vehicle underwent maintenance and did not collect any information. Also, some adjustments were required to the onboard DAS at certain times during the FOT, and the device did not collect any information during these periods). Figure 111 presents the weight information collected by this vehicle during the Part 2 MTDC FOT. Each point on that figure represents an observed load condition (GVW) for a given trip. This GVW was computed as the sum of the average of the weigh sensor data for each axle between two loading-change points (i.e., between points at which the vehicle came to a stop and its load changed substantially, and at which the PTO was activated). The horizontal axis in the figure indicates elapsed time since an arbitrary point (July 1, 2010), which was about a month earlier than the start date of the FOT for this vehicle. For any given day or longer period of time, there is almost always a reading from the vehicle while it is in the empty condition (bottom of the chart) and a series of points that could be from 2,000 to 16,000 lb heavier than the empty condition, indicating the load that the vehicle was carrying.

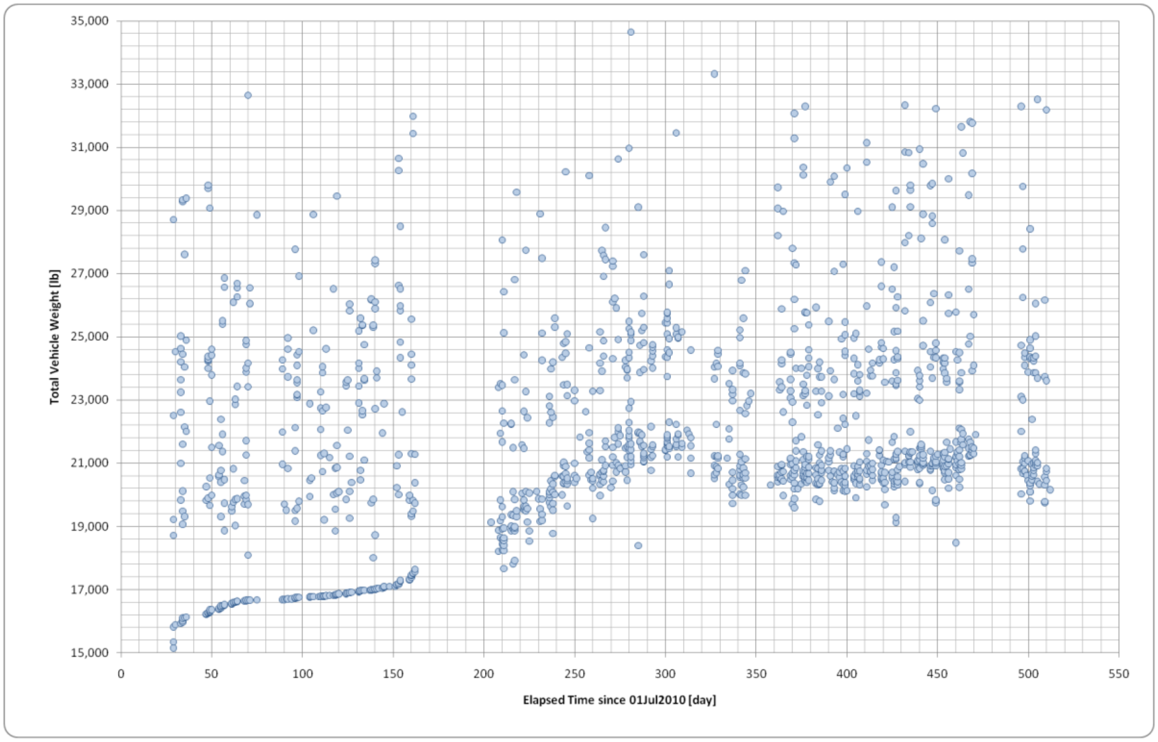

Figure 111. Towing and recovery truck 3 (MTDC vehicle 12) GVW.

Figure 111shows three distinct areas. The first area, from the start of the FOT to about day 160, shows very small variability for the "empty vehicle" condition, with a slowly increasing tendency as a function of time. The manufacturer of the weigh-data collection device attributed this tendency to a settling or adjustment period. That was followed by a period of just over a month in which data was not collected, for reasons explained previously. However, when data collection was reinitiated, the weight data underwent a rapid and significant increase tendency, which also showed more variability (e.g., compare the "vehicle empty" condition for the first and second data blocks). This increasing gross weigh tendency somehow stabilized after day 320. However, the variability did not disappear. One explanation of this behavior given to the ORNL researchers by the manufacturer of the device was that the sensor(s) may have been subject to a significant force (e.g., the vehicle hitting a curb) that somehow loosened the sensors, resulting in the observed variability. It was not possible for the ORNL researchers to corroborate this explanation.

Nevertheless, a visual observation of the data indicated that the bias (increasing total vehicle weigh tendency as a function of time) was systematic; therefore, an effort was made to eliminate it. To do so, three distinct regions were identified and the "empty-vehicle" condition was selected for the development of linear regression models that were used to correct the data bias (see Figure 112). The "empty-vehicle" condition was selected because it was the only condition for which there was known data that was exogenous to the AirWeigh device. That is, that condition is easy to identify in the collected data since it is the condition with the least reported GVW. Also, it was known from the calibration procedures performed at the beginning of the FOT what the readings should have been for that condition (i.e., 16,750 lb, see Table 28 and Subsection 5.2.1 Weight)

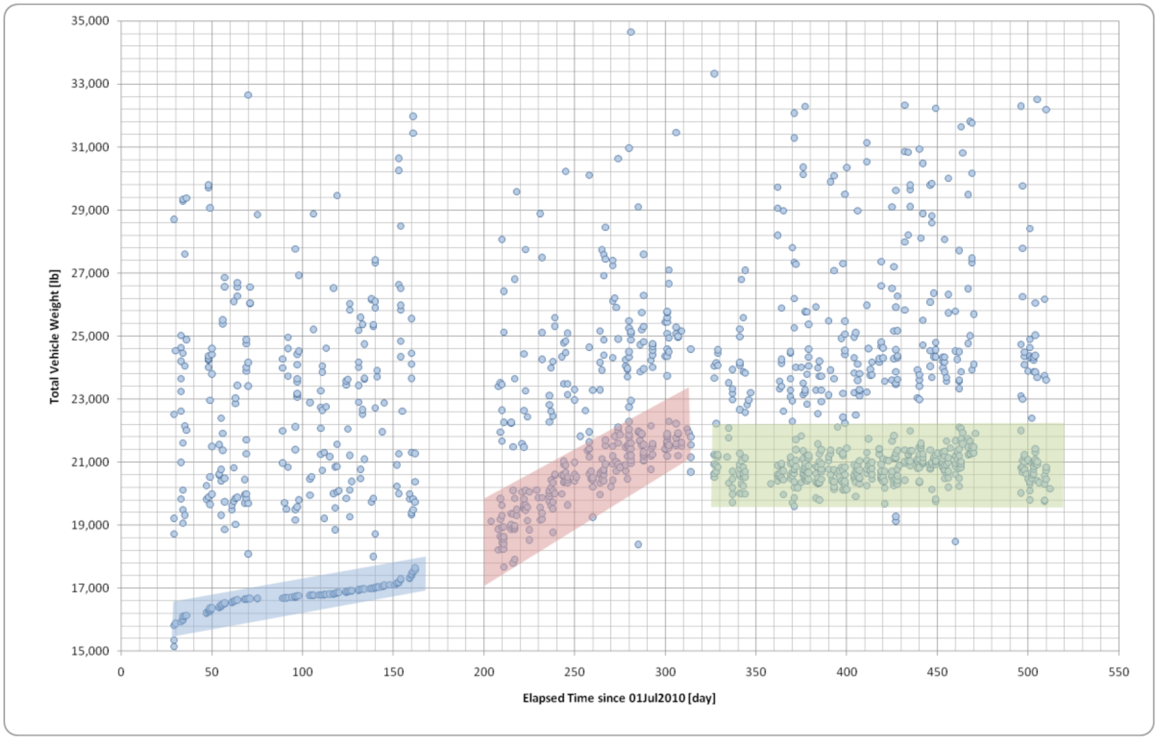

Figure 112. Towing and recovery truck 3 (MTDC vehicle 12) GVW vs. time, "empty-vehicle" condition regions.

For each one of these three regions, and using the data identified as "empty vehicle" (i.e., bottom of the graph for each region), three linear regression models were developed and used to correct the collected weight data. These three models, presented in Figure 113, were used as follows. Consider, for example the second region, and within that region, day 250. For that day, the model indicates that there was a bias of 2,900 lb [i.e., (27.862 * 250 + 13,381) – 16,750], so 2,900 lb was subtracted from each one of the day-250 observations.

This procedure was repeated for all the data collected; the results are presented in Figure 114. The figure shows that the systematic bias was corrected by application of the methodology described here. To eliminate the effects of the variability in the data observed in regions 2 and 3, the weight of the vehicle was divided into four categories: (1) empty vehicle (GVW less than 18,500 lb), (2) light load (GVW between 18,500 and 22,500 lb), (3) medium load (GVW between 22,500 and 25,500 lb), and (4) heavy vehicle load (GVW greater than 25,500 lb). The boundaries for these four categories were not arbitrary but were obtained from the distribution of collected GVWs shown in Figure 115. In that figure, it is possible to see that there are four distinct distributions (or a single distribution with four modes). The boundaries of these sub-distributions were used to determine the weight classification introduced above.

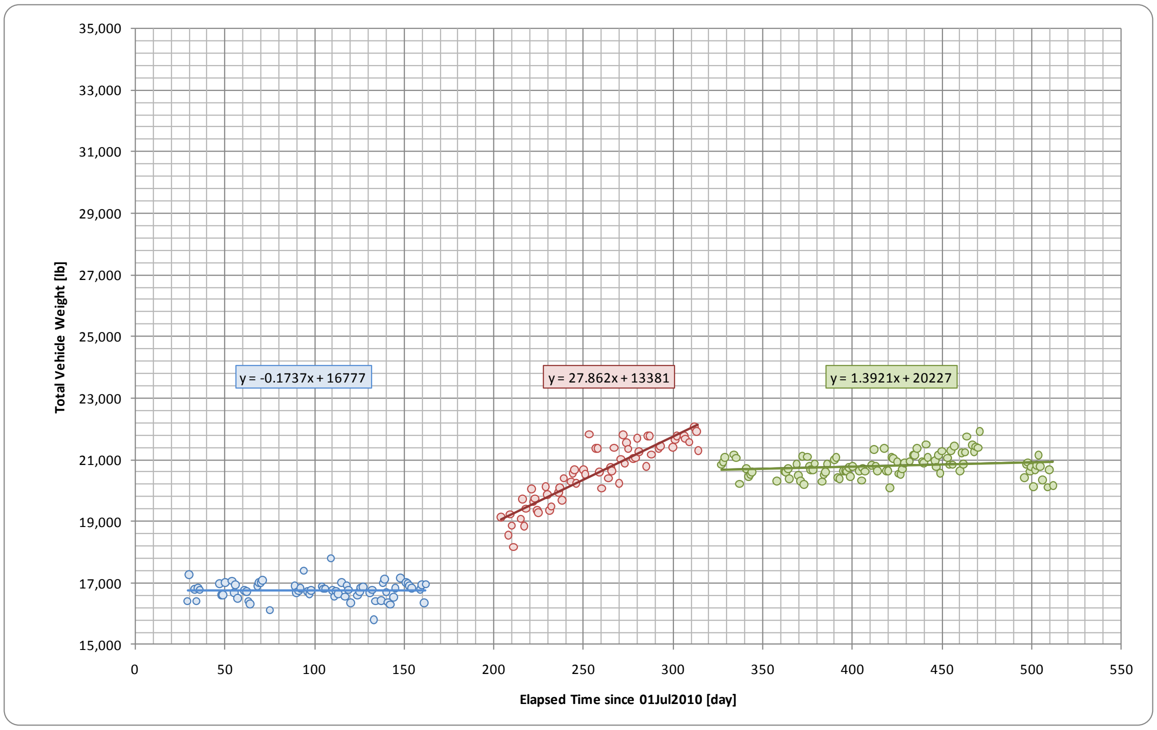

Figure 113. Towing and recovery truck 3 (MTDC vehicle 12) GVW vs. time, linear regression models for the three "empty-vehicle" condition regions.

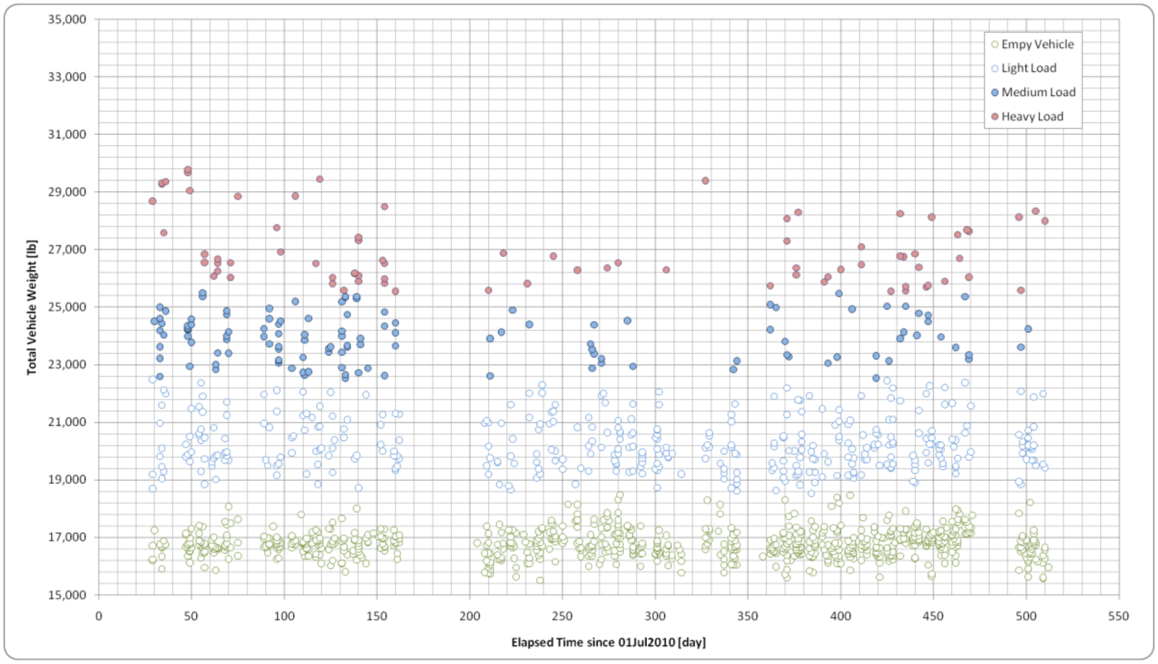

Figure 114. Towing and recovery truck 3 (MTDC vehicle 12) GVW vs. time, adjusted weight data.

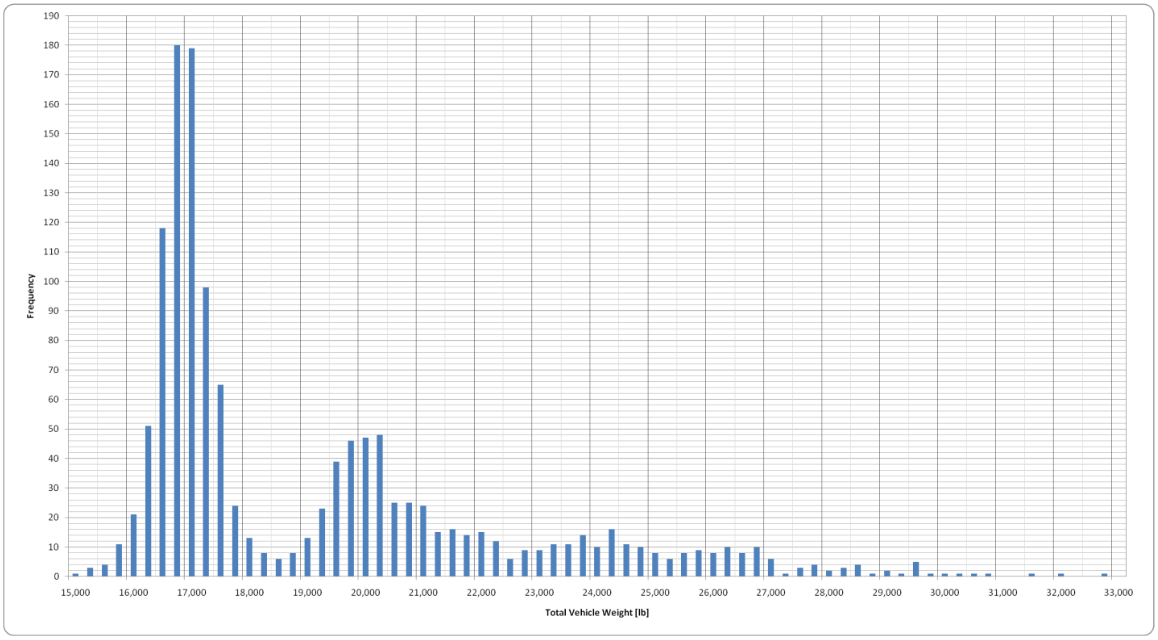

Figure 115. Towing and recovery truck 3 (MTDC vehicle 12) distribution of GVW.

5.4.2 Effect of Vehicle Weight on Fuel Efficiency

This subsection introduces the weight of the vehicle, as a controlling variable, to study how the payload affects the FE of towing and recovery trucks. Before discussing the results, however, an analysis is presented wherein a statistical comparison is made to determine whether it is possible to use all of the data introduced in the previous subsection (i.e., data from the three regions) or just data from the first region (i.e., extending from day 0 to day 160 in Figure 111). This is done because the first region showed very little variability of the data, whereas the variability in the data for the second and third regions was more pronounced. The statistical analysis consists in a test of hypothesis in which each of the four distributions of payload level generated using the data collected during the first part of the tests and without any corrections (day 0 to day 165 in Figure 111) is compared with the same four distributions generated using all of the data after the corrections described were introduced. A rejection of the null hypothesis would imply that the distributions are different.

Table 35 and Table 36 present the parameters defining the GVW distributions for the four categories considered. Those parameters were computed using just the first third of the data (first region or Data Set 1 in Figure 111) with no corrections (Table 35) and with all of the data with the corrections applied (Table 36). For each weight-level category, each pair of distributions corresponding to the first third of the data, with no weight correction, and all of the data with corrections was then compared. To do so, the null hypothesis H_0, stating that the means of the distributions were the same, was statistically tested. The results are presented in Table 37. The null hypothesis H_0 could be rejected only with less than 85% confidence, thus strongly suggesting that the distributions were similar to one another. Therefore, all of the data collected and corrected using the methodology explained in the previous subsection could be used to analyze the impact of vehicle payload on the FE of the towing and recovery vehicles.

Table 35. Distribution parameters for four GVW categories (first third of the data collected—no correction)

Statistics	Empty vehicle	Light load	Medium load	Heavy load
Number of observations	206	101	79	38
Minimum	15,816	18,718	22,529	25,556
Maximum	18,086	22,511	25,514	29,800
Mean	16,778	20,341	23,964	27,226
Standard deviation	370	930	805	1,375
Duration [h]	158	55	39	20

Table 36. Distribution parameters for four GVW categories (all of the data collected—weight correction applied)

Statistics	Empty vehicle	Light load	Medium load	Heavy load
Number of observations	774	376	123	79
Minimum	15,511	18,523	22,526	25,557
Maximum	18,489	22,490	25,497	29,782
Mean	16,783	20,239	23,933	26,973
Standard deviation	472	906	799	1,201
Duration [h]	1,022	794	1,178	1,561

Table 37. Comparison of distributions for four GVW categories (first third of the data collected without correction vs. all of the data collected with weight correction applied)

Statistics	Empty vehicle		Light load		Medium load		Heavy load	
	Data set 1	All data	Data set 1	All data	Data set 1	All data	Data set 1	All data
Mean	16,778	16,783	20,341	20,239	23,964	23,933	27,226	26,973
Standard deviation	370	472	930	906	805	799	1375	1201
No. of observations	206	774	101	376	79	123	38	79
Delta mean		-5.3		102.1		30.3		253.1
Std dev diff		30.86		103.63		115.76		260.79
Z		-0.17		0.98		0.26		0.97
P-value		0.57		0.16		0.40		0.17
Reject Ho at confidence level =		**50.0%**		**83.8%**		**60.3%**		**83.4%**

To generate the distributions of FEs corresponding to the trips that were identified in each one of the four GVW categories, only those trips longer than 10 miles were considered. A FE observation was computed as the ratio of the distance traveled in each specific trip considered divided by the fuel consumed in that trip (both computed with information obtained from the vehicle data bus during the FOT). Trips involving short distances (less than 10 miles) introduce large variability in the FE and therefore were not considered. This reduced the number of observations in some cases by half (e.g., the 774 empty vehicle trips were reduced to 363), although in all cases the number of observations was still large.

A summary of the distributions of FE, distance traveled, and fuel consumed in trips longer than 10 miles for each of the four vehicle payload categories is presented in Table 38. The mean of the FEs for each of the payload categories was computed as the mean of the distribution of the FEs, with each trip providing one observation (e.g., there were 363 FE observations for the empty vehicle category). These FE means are slightly different from an average FE computed by dividing the total distance by the total fuel consumed for any of the four payload categories. Table 39 presents the weight difference between the empty vehicle and the other three payload categories, as well as the total distance traveled with an empty vehicle and with the vehicle loaded. These two distance traveled are roughly the same (approximately a 10% difference), which would be expected for towing and recovery operations.

Table 38. Fuel efficiency, distance traveled, and fuel consumed distribution parameters as a function of four GVW categories

	Statistics	Empty vehicle	Light load	Medium load	Heavy load
FE [mpg]	Number of observations	363	183	64	54
	Minimum	3.66	5.90	6.05	6.00
	Maximum	12.95	12.58	12.77	12.64
	Mean	9.87	9.74	9.34	8.91
	Standard deviation	1.35	1.12	1.16	1.27
Distance traveled [mile]	Number of observations	363	183	64	54
	Minimum	10	10	10	11
	Maximum	367	420	376	228
	Mean	30	32	31	43
	Standard deviation	38	47	47	45
TOTAL DISTANCE [mile]		**11,006**	**5,771**	**1,961**	**2,305**
Fuel consumption [gal]	Number of observations	363	183	64	54
	Minimum	0.81	0.99	1.01	1.27
	Maximum	33.54	43.35	51.76	25.53
	Mean	2.98	3.19	3.42	4.70
	Standard deviation	3.43	4.65	6.36	4.82
TOTAL FUEL [gal]		**1,081**	**584**	**219**	**254**

Table 39. Distance traveled and weight difference with respect to the empty vehicle condition for four GVW categories

Statistics	Empty vehicle	Light load	Medium load	Heavy load
Distance traveled [mile]	11,006	10,037		
Weight difference [lb]*	0	3,456	7,150	10,190
Weight difference [lb]**	33	3,489	7,183	10,213

Table 38 shows that, as expected, the FE worsens as the payload increases. A test of hypothesis was performed to determine if there were statistically significant differences between the FE distributions of the empty vehicle condition and any of the other three payload levels. The results of the test of hypothesis are presented in Table 40. For both the medium and heavy load levels, the null hypothesis of equal means of the distributions of FE for those cases and the empty-vehicle case could be rejected with more than 99% confidence. This strongly suggested the distributions of FEs were different and therefore the vehicle payload made a statistically significant difference in FE. In the case of empty-vehicle vs. light load, the null hypothesis could be rejected only with less than 90% confidence, suggesting there is not a significant difference between the mean FE when the vehicle is empty and when the vehicle is carrying a light load. In summary, medium and heavy loads as defined here can have impact significant impacts in the reduction of FE for the towing and recovery vocation.

Table 40. Comparison of fuel efficiency distributions for four GVW categories

Statistics	Empty vehicle	Light load	Medium load	Heavy load
Mean [mpg]	9.87	9.74	9.34	8.91
Standard deviation [mpg]		0.1090	0.1610	0.1865
Number of observations	363	183	64	54
Delta mean		0.13	0.52	0.96
Standard deviation difference		0.1090	0.1610	0.1865
Z		1.1734	3.2545	5.1592
P-value		0.12	0.00	0.00
Reject Ho at confidence level =		**88.0%**	**99.9%**	**99.9%**

5.5 POWER TAKEOFF OPERATIONS

Both the utility vehicles and the towing and recovery trucks had additional equipment (i.e., a bucket for the former, and a rollback flatbed and winch for the latter) that required PTO operation. A substantial proportion of the vehicles' idling time occurred during PTO operation, especially for the utility vehicles. This subsection presents some statistics regarding idling time with and without PTO operation for the six vehicles, as well as the distributions of idling time and idling fuel as a function of the vehicle engine speed.

5.5.1 Utility Vehicle PTO Operation

The distribution of idling time and fuel consumed while idling presented in Table 31 was further divided into idling with PTO off (i.e., regular idling while operating the vehicle in traffic, such as at traffic lights) and idling with the PTO on (i.e., idling when the PTO equipment was engaged). The results are presented in Table 41 and Table 42. Notice that although the number of idling hours for the PTO-on condition was almost half that of the PTO-off state, the fuel consumed while idling was only 7% lower for the latter than for the former. That is, in the PTO-on state, the vehicles consumed about 1.5 gal/h while idling, vs. 0.9 gal/h in the PTO-off state (i.e., idling in traffic).

Table 41 and Table 42 also show that in the PTO-off case, two-thirds of the time and fuel consumed while idling corresponded to idling intervals of less than 1 h. In the PTO-on case, more than 70% of the time and fuel consumed while idling corresponded to intervals longer than 1 h.

Table 41. Distributions of time spent and fuel consumed while idling (utility vehicles—PTO off)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	110.7	13.7	5.0	108.1	14.9	2.1
5–15	83.6	10.3	3.8	74.7	10.3	1.5
15–60	338.5	41.9	15.4	309.9	42.7	6.1
60–120	188.5	23.3	8.6	162.6	22.4	3.2
120–180	61.2	7.6	2.8	51.7	7.1	1.0
180–240	20.6	2.6	0.9	15.1	2.1	0.3
240+	4.8	0.6	0.2	3.7	0.5	0.1
TOTAL	**808**	**100**	**36.8**	**726**	**100**	**14.4**

Table 42. Distributions of time spent and fuel consumed while idling (utility vehicles—PTO on)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	4.6	1.2	0.2	6.7	1.0	0.1
5–15	18.1	4.3	0.8	31.8	4.7	0.6
15–60	84.5	19.6	3.9	139.3	20.6	2.8
60–120	103.9	22.4	4.7	166.0	24.6	3.3
120–180	81.2	15.5	3.7	112.1	16.6	2.2
180–240	56.8	14.5	2.6	75.1	11.1	1.5
240+	103.2	22.4	4.7	144.5	21.4	2.9
TOTAL	**452**	**100.0**	**20.6**	**676**	**100.0**	**13.4**

The time spent and fuel consumed while idling under PTO-off and PTO-on operation were also distributed as a function of engine speed intervals. Figure 116 to Figure 121 show these distributions for each of the three utility vehicles participating in the project for the PTO-off (116, 118, and 120) and PTO-on (117, 119, and 121) conditions. In all cases, engine speed is divided into 100 rpm intervals, starting at 700 rpm. The hatched bars show the distribution of idling time, and the solid bars present that of idling fuel.

As expected, the distributions for the PTO-off case are very similar for the three vehicles. However, for MTDC vehicles 8 and 9, which are very similar vehicles, there is a slight difference in the distribution for both time and fuel consumed for the last engine interval (2300+ rpm). Vehicle 9 shows a higher percentage than vehicle 8. This is likely attributable to driving behavior and resulted in a higher hourly fuel consumption for vehicle 9 than for vehicle 8 (see Table 43). For the PTO-on condition, vehicle 7 shows a slight difference with respect to the PTO-off condition, with the mean of the distributions (especially that of fuel consumed while idling) slightly moving to the right (i.e., higher engine rpm). The other two vehicles show very different distributions from the PTO-off case, with a very high percentage of time and fuel consumed in the 1,100 to 1,300 rpm interval and with hourly fuel consumption similar to that shown in Table 43.

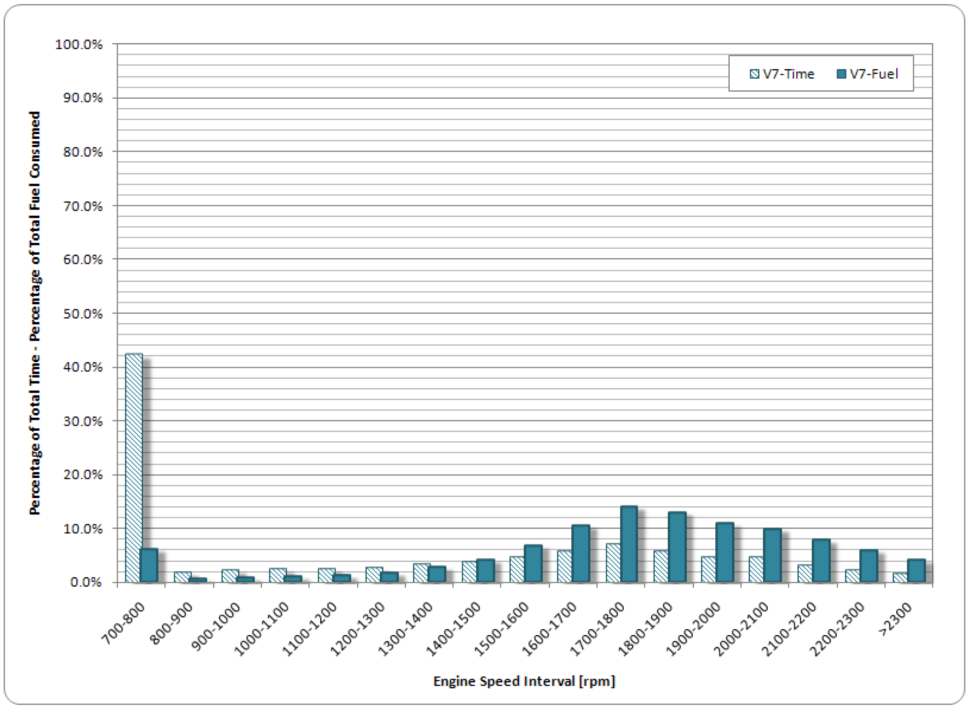

Figure 116. Utility vehicle 1 (MTDC vehicle 7) distribution of idling time and idling fuel consumed—PTO off.

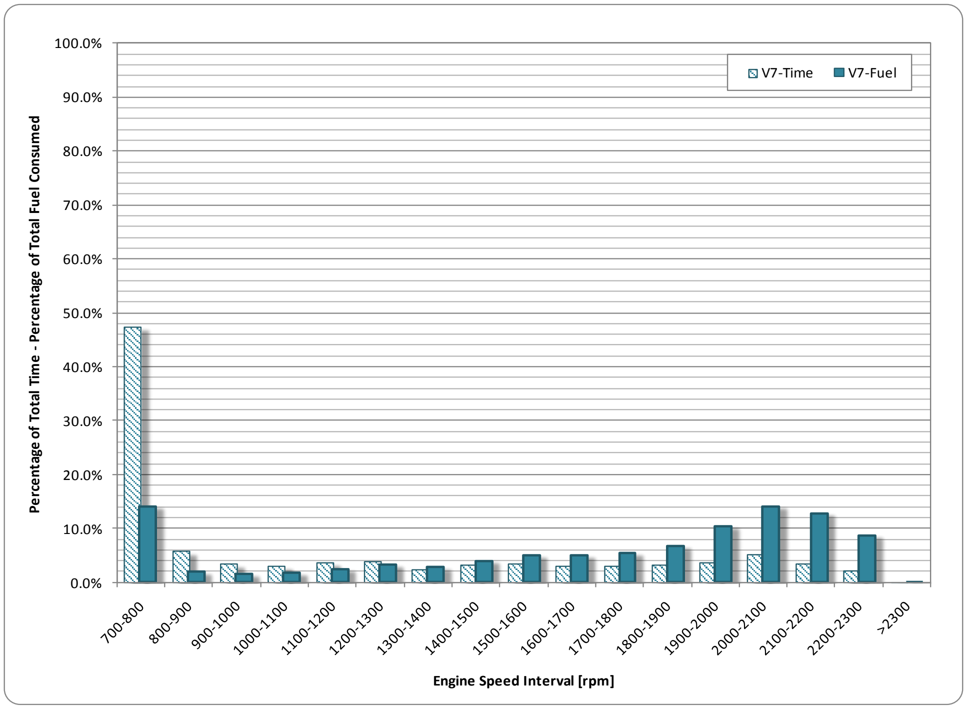

Figure 117. Utility vehicle 1 (MTDC vehicle 7) distribution of idling time and idling fuel consumed—PTO on.

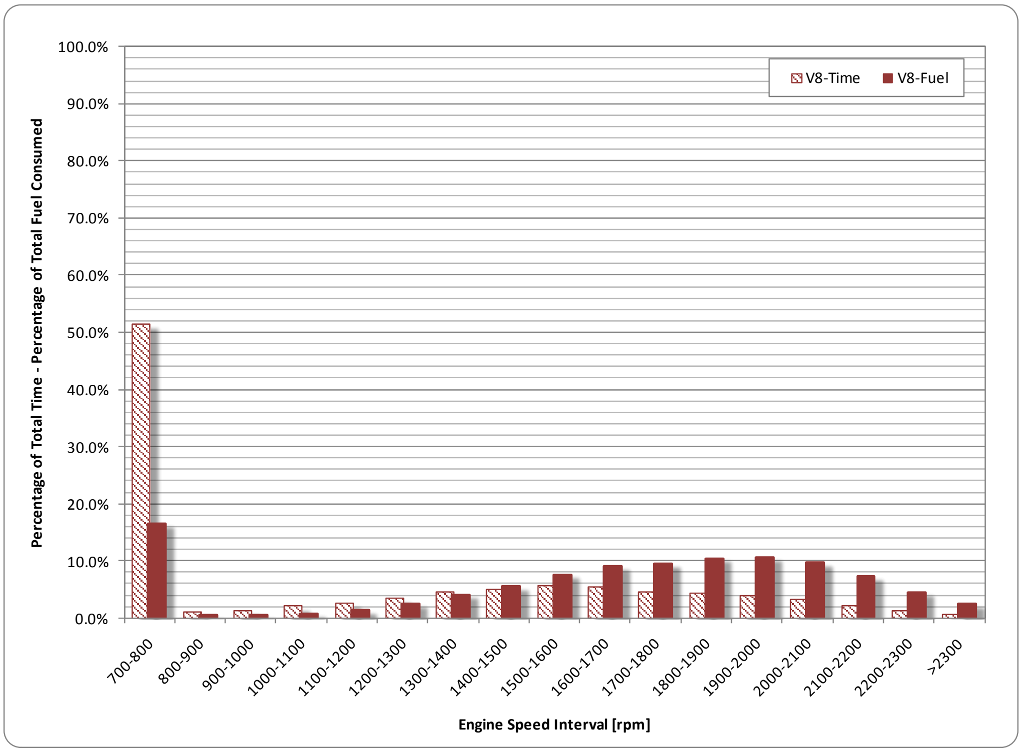

Figure 118. Utility vehicle 2 (MTDC vehicle 8) distribution of idling time and idling fuel consumed—PTO off.

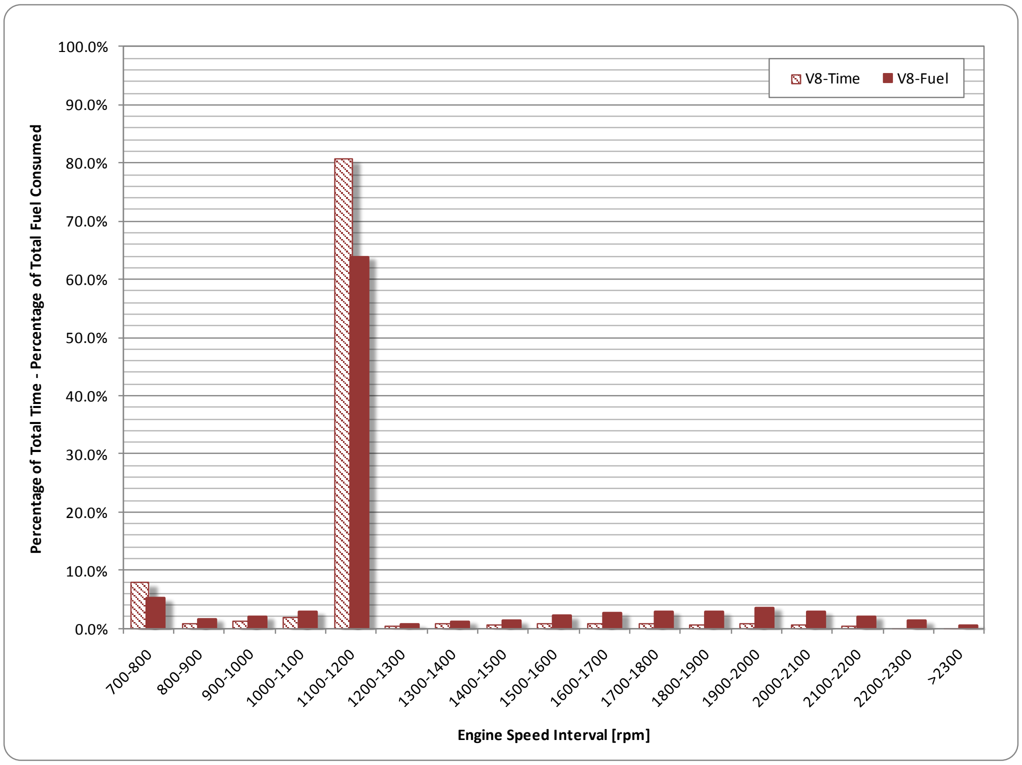

Figure 119. Utility vehicle 2 (MTDC vehicle 8) distribution of idling time and idling fuel consumed—PTO on.

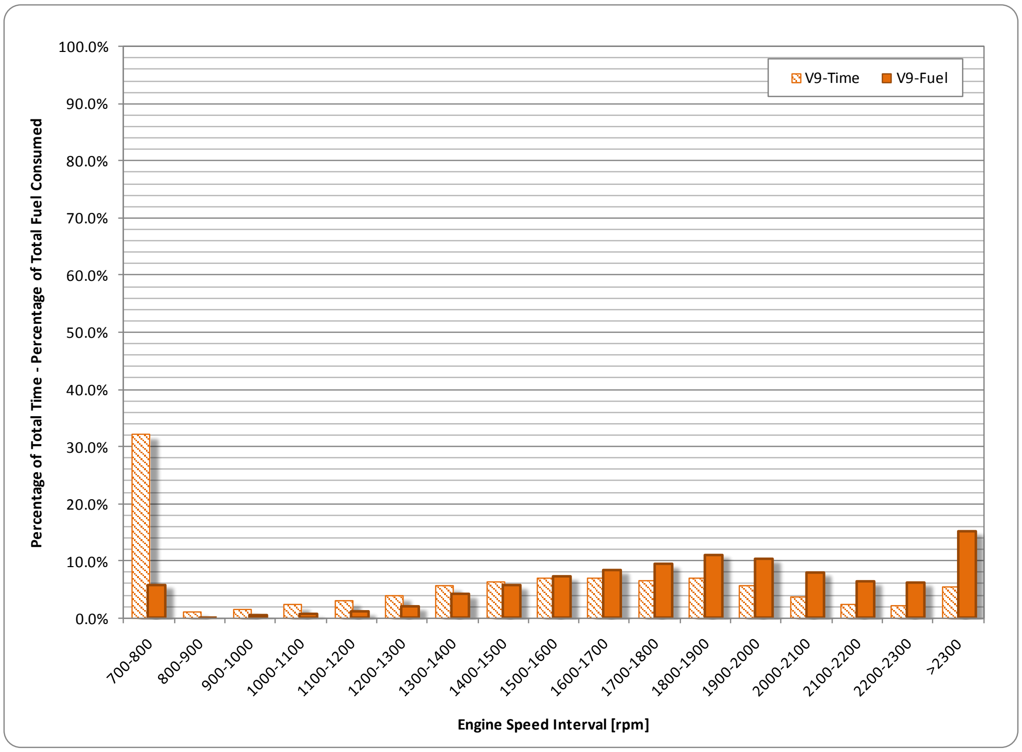

Figure 120. Utility vehicle 3 (MTDC vehicle 9) distribution of idling time and idling fuel consumed—PTO off.

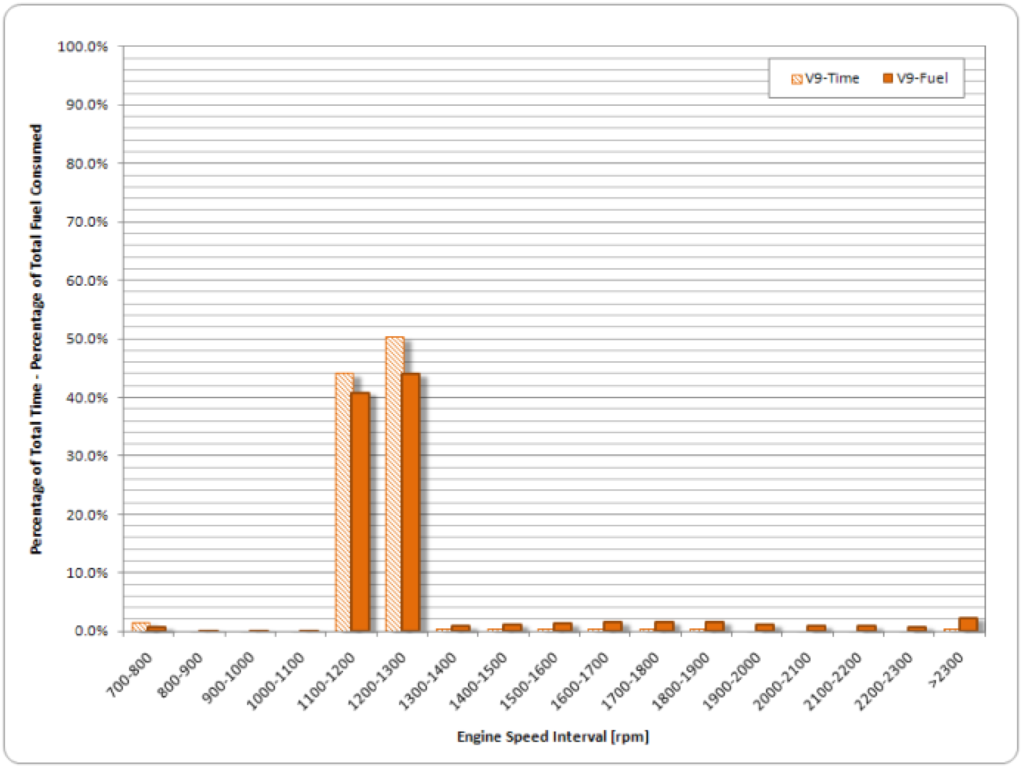

Figure 121. Utility vehicle 3 (MTDC vehicle 9) distribution of idling time and idling fuel consumed–PTO on.

Table 43. Hourly fuel consumption (gph) (utility vehicles—PTO off and on)

PTO condition	MTDC vehicle		
	7	8	9
PTO off	4.98	3.91	5.07
PTO on	1.95	2.21	2.00

5.5.2 Towing and Recovery Truck PTO Operation

The distribution of idling time and fuel consumed while idling for the towing and recovery trucks, presented in Subsection 5.3.1 (see Table 32), was further divided into idling with PTO-off and PTO-on conditions. These additional distributions are shown in Table 44 and Table 45. As was the case with the utility vehicles, the towing and recovery trucks showed that although the number of idling hours for the PTO-on condition was less than half that for PTO-off, the fuel consumed while idling was only 8% lower when the PTO equipment was engaged than when it was not.

44 and 45 also show that almost two-thirds of the idling, in terms of time and fuel consumed, with the PTO off was due to traffic congestion (less than 15 min idling interval). In the PTO-on case, almost 90% of the idling time and fuel was spent in intervals longer than 15 min.

Table 44. Distributions of time spent and fuel consumed while idling (towing and recovery trucks—PTO off)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	306.5	37.4	10.1	184.4	37.9	2.3
5–15	229.2	28.0	7.5	108.7	22.4	1.3
15–60	227.5	27.8	7.5	143.0	29.4	1.8
60–120	53.3	6.5	1.8	46.1	9.5	0.6
120–180	2.7	0.3	0.1	4.2	0.9	0.1
180–240	0.0	0.0	0.0	0.0	0.0	0.0
240+	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**819**	**100**	**27.0**	**486**	**100**	**6.0**

Table 45. Distributions of time spent and fuel consumed while idling (towing and recovery trucks—PTO on)

Idling interval [min]	Time spent			Fuel consumed		
	[h]	Percent of total idling time	Percent of total time	[gal]	Percent of total idling fuel	Percent of total fuel
0–5	6.7	1.7	0.2	7.7	1.7	0.1
5–15	43.2	11.0	1.4	48.7	10.8	0.6
15–60	269.8	68.5	8.9	307.0	68.3	3.8
60–120	73.9	18.8	2.4	85.9	19.1	1.1
120–180	0.0	0.0	0.0	0.0	0.0	0.0
180–240	0.0	0.0	0.0	0.0	0.0	0.0
240+	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**394**	**100.0**	**13.0**	**449**	**100.0**	**5.5**

Idling time and idling fuel consumed for PTO-off and PTO-on operation were also distributed as a function of engine speed intervals. 122 to 127 present these distributions for each one of the three towing and recovery trucks that participated in this project. In all of these figures, engine speed is divided into 100 rpm intervals (starting at 700 rpm); the hatched bars present the distribution of idling time, and the solid bars show the distribution of idling fuel consumed. As expected, the distributions for the PTO-off case are very similar for the three vehicles, but especially for vehicles 11 and 12, which were almost identical (except for their transmissions). The hourly fuel consumption while idling in the PTO-off condition was 3.5 and 3.4 gph for vehicles 8 and 9, respectively (see Table 46). However, under the PTO-on condition, the distributions of idling time and idling fuel consumed as a function of engine speed were quite different (see Figure 125 and Figure 127) and resulted in an almost 24% higher hourly idling fuel consumption for vehicle 11 than for vehicle 12 (1.20 gph vs. 0.97 gph, see Table 46). On vehicle 11, the PTO equipment was operated at a higher rpm (1,550 rpm on average) than on vehicle 12 (1,150 rpm on average).

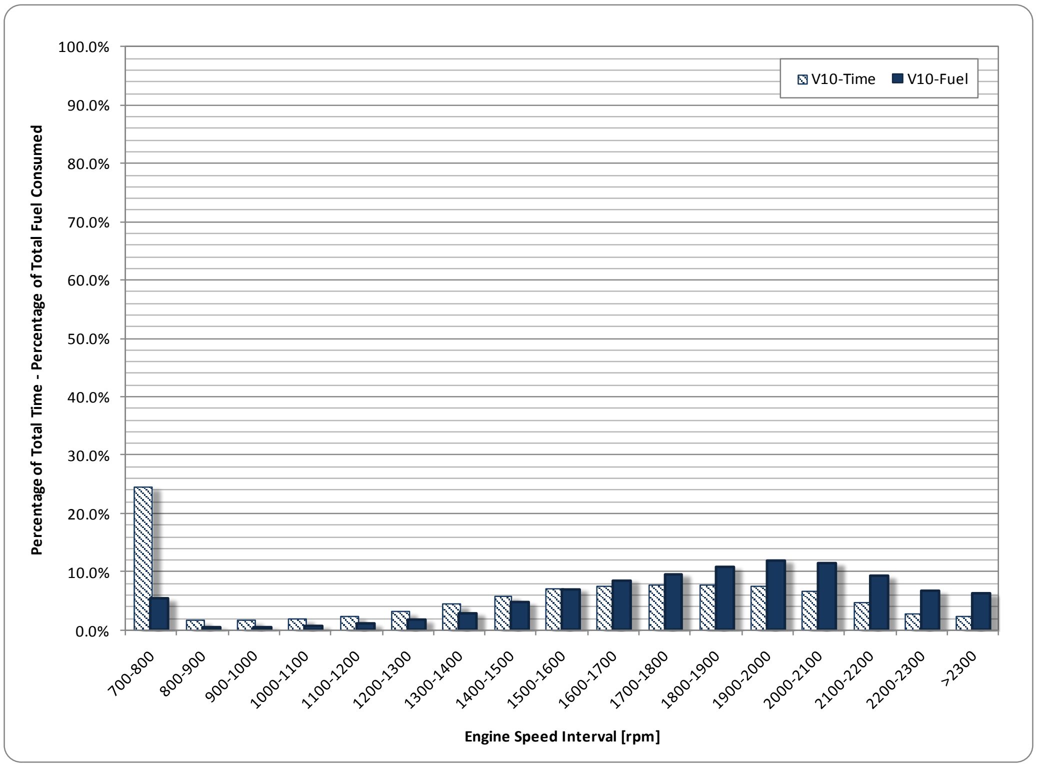

Figure 122. Towing and recovery truck 1 (MTDC vehicle 10) distribution of idling time and idling fuel consumed—PTO off.

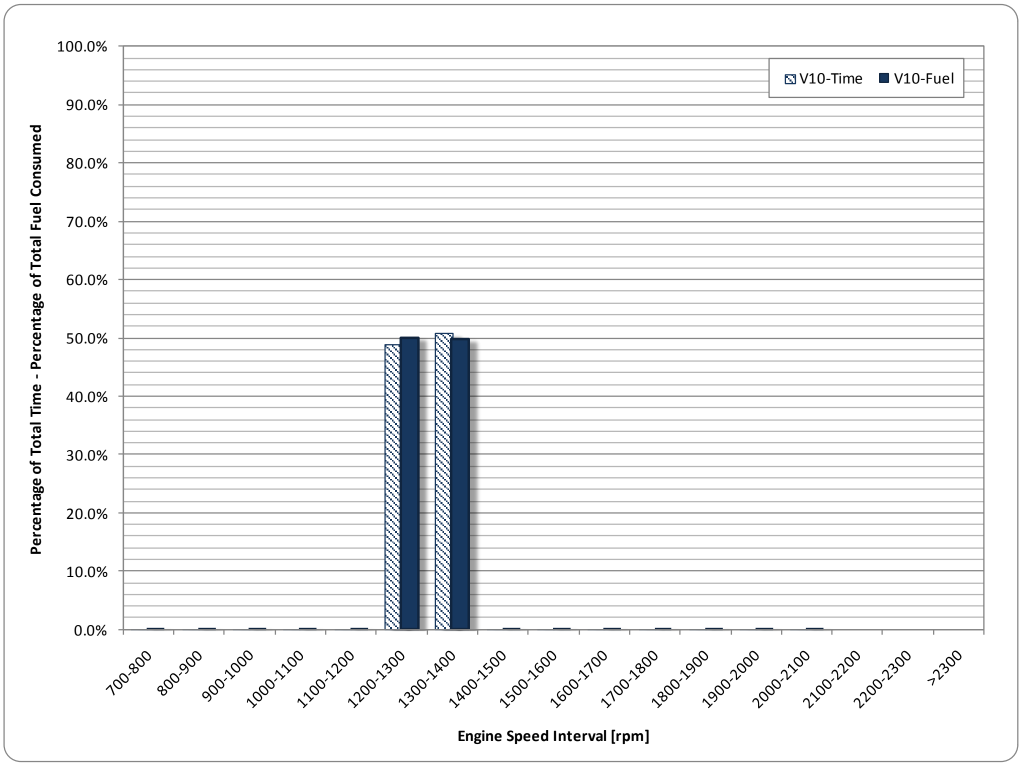

Figure 123. Towing and recovery truck 1 (MTDC vehicle 10) distribution of idling time and idling fuel consumed—PTO on.

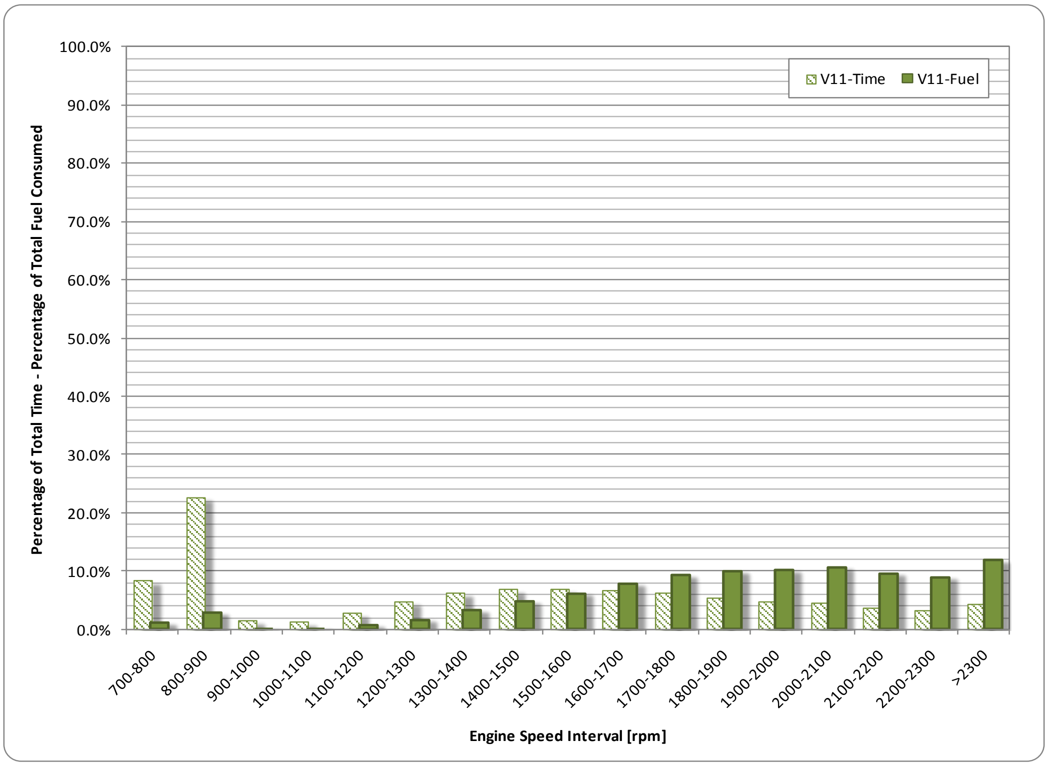

Figure 124. Towing and recovery truck 2 (MTDC vehicle 11) distribution of idling time and idling fuel consumed—PTO off.

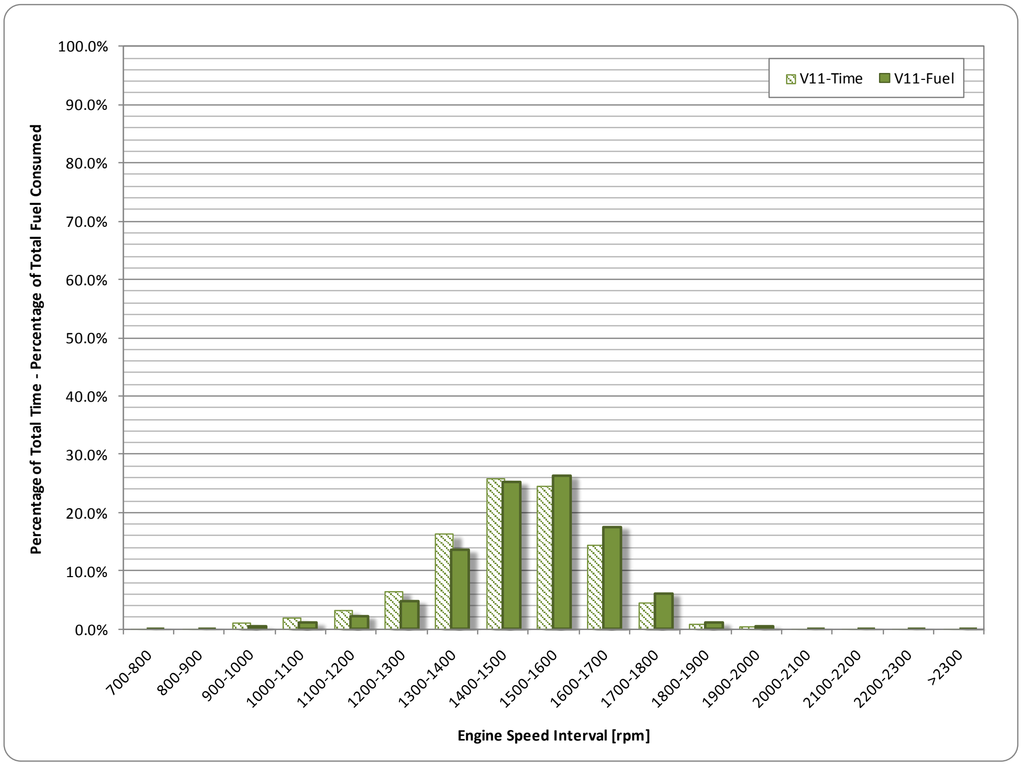

Figure 125. Towing and recovery truck 2 (MTDC vehicle 11) distribution of idling time and idling fuel consumed—PTO on.

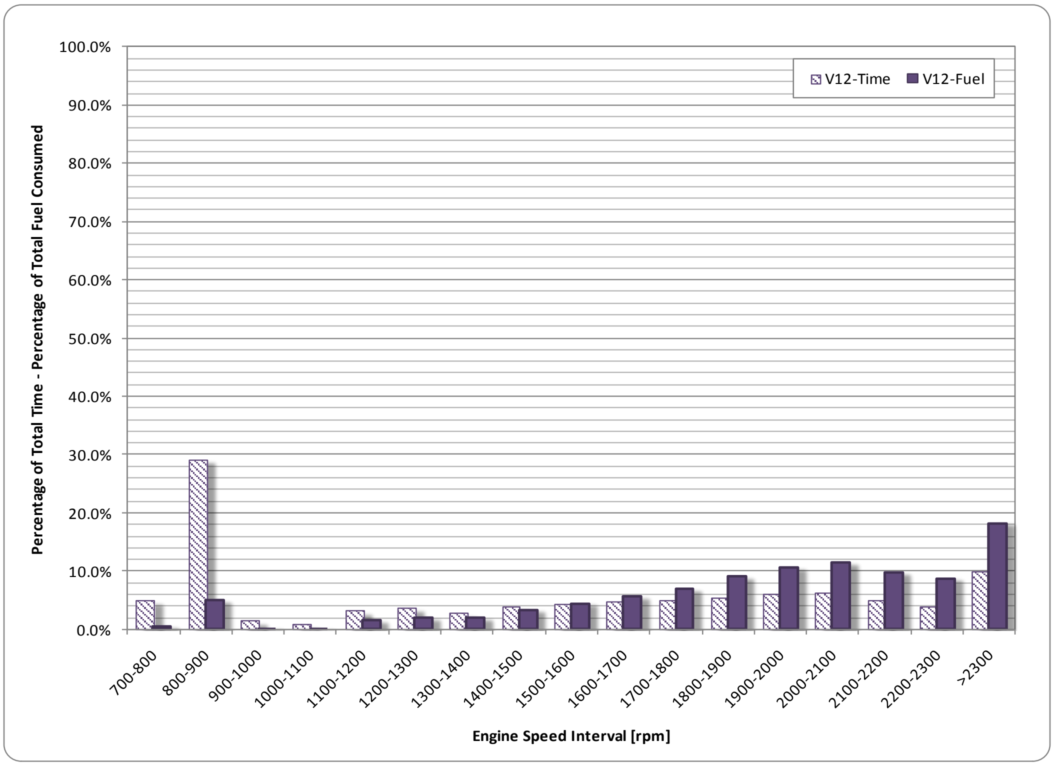

Figure 126. Towing and recovery truck 3 (MTDC vehicle 12) distribution of idling time and idling fuel consumed—PTO off.

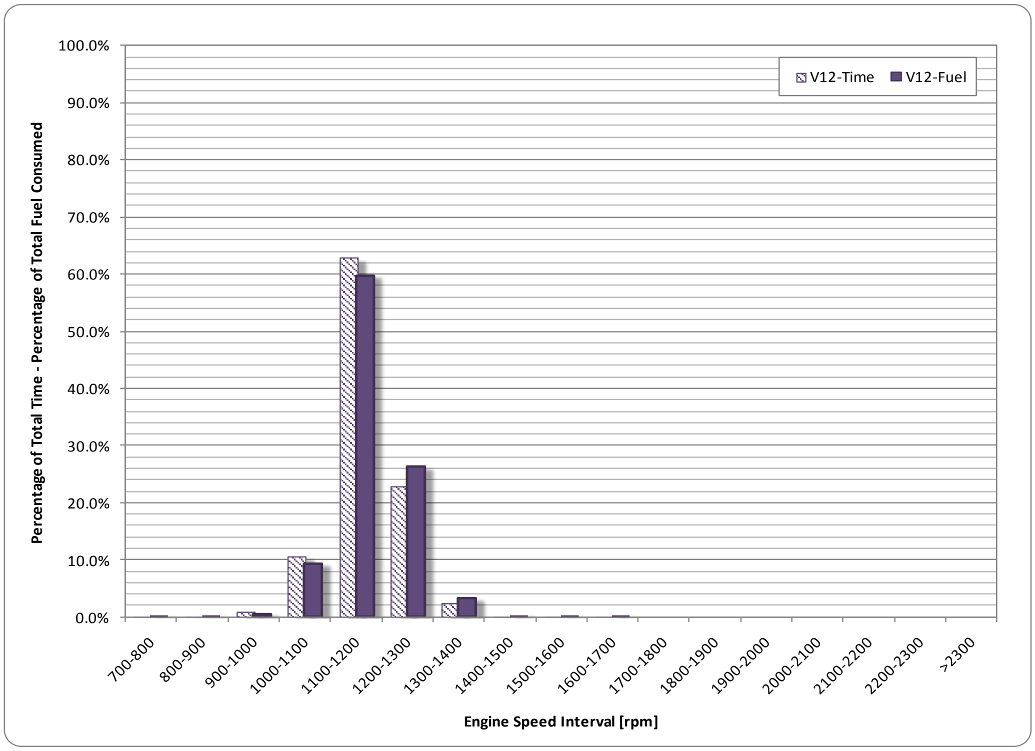

Figure 127. Towing and recovery truck 3 (MTDC vehicle 12) distribution of idling time and idling fuel consumed—PTO on.

Table 46. Hourly fuel consumption [gph] (towing and recovery trucks—PTO off and on)

PTO condition	MTDC vehicle		
	10	11	12
PTO off	4.11	3.35	3.45
PTO on	1.85	1.20	0.97

5.6 VEHICLE STOPS

All of the four vocations that participated in the MTDC FOTs had the characteristic of needing to stop many times during their daily operations. The data collected in these FOTs was used to obtain distributions of daily stop frequency and length of stops. This information, which is presented and discussed in the next subsections, is generally not available in the open literature. It is also very important for modelers who study loss of roadway capacity (e.g., a utility vehicle repairing electrical lines and blocking one lane) that causes increased congestion and therefore has secondary fuel consumption effects. They are also important for modeling pollution and other related measures associated with stops while idling.

The next subsection presents summary information regarding roadway type use (i.e., freeways vs. surface streets) and length of stopped time, by vocation. The two subsequent subsections deal with the distribution of daily stops and of the lengths of stops, respectively, for all of the four vocations that participated in the MTDC Project.

5.6.1 Roadway Utilization

As opposed to the vehicles participating in the HTDC FOT (i.e., long-haul Class-8 trucks), which spent over 90% of their time on freeway-type roads, the MTDC vehicles ranged from a minimum of 2% of their total moving time on freeways (transit buses) to a maximum of 41% (combination trucks). The other two vocations, utility vehicles and towing and recovery trucks, were somewhere in between, with a range of 10–15% for the former and 15–26% for the latter. This information is presented in Table 47, together with the percentage of moving time spent on surface streets for each one of the 12 vehicles that participated in the MTDC FOTs and an overall percentage for each vocation. The overall percentage for each vocation was computed considering the total moving time logged by each group of three vehicles on freeways and surface streets.

For each of the four vocations, Table 47 also presents the percentage of stops with the engine running that lasted 1, 2, and 3 min or less and, implicitly, the percentage of stops that lasted more than 3 min (i.e., 100 minus the percentage of stops that were 3 min or less). On average, the combination trucks and transit vehicles showed that 80% or more of the stops they made lasted 3 min or less, and more than 70% of the stops were less than 2 min.[23] Those are typical stops at traffic lights or other types of delays related to traffic. For the other two vocations (utility vehicles and towing and recovery vehicles), these proportions were lower; that is, about 55% to 57%, on average, were stops that lasted less than 3 min. Although these two vocations spend a high percentage of their moving times on surface streets (see Table 47) and therefore should present a high number of stops at traffic lights and other signalized intersections, their operations that required the use of PTO equipment resulted in many stops that lasted much longer than 3 min. This information is also presented graphically in Figure 128.

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[23] The combination trucks made many stops that lasted longer than 3 min while conducting their normal business (i.e., delivery of goods). However, they turned their engines off and therefore are not included in Table 47.

Table 47. Roadway type use and percent of stops by stop-time length

MTDC vehicle type	MTDC vehicle number	Percent of total moving time		Percent of stops		
		On freeways	On surface streets	1 min or less	2 min or less	3 min or less
Combination trucks	1	31.4	68.6	32.1	67.6	81.3
	2	38.2	61.8	47.6	80.6	88.3
	3	40.9	59.1	43.3	74.3	85.4
	1-3	37.0	63.0	40.7	74.0	84.9
Transit buses	4	3.9	96.1	51.1	72.9	81.4
	5	4.1	95.9	40.4	61.4	73.3
	6	1.8	98.2	50.1	71.9	79.7
	4-6	3.2	96.8	48.7	70.4	79.3
Utility vehicles	7	15.0	85.0	29.7	46.8	52.9
	8	9.6	90.4	36.0	53.2	58.6
	9	10.2	89.8	35.8	53.7	58.4
	7-9	10.9	89.1	34.3	51.7	57.1
Towing and recovery trucks	10	15.5	84.5	32.0	49.1	56.0
	11	15.7	84.4	32.2	46.8	53.8
	12	26.2	73.8	32.1	48.2	54.8
	10-12	19.4	80.6	31.9	47.8	54.6

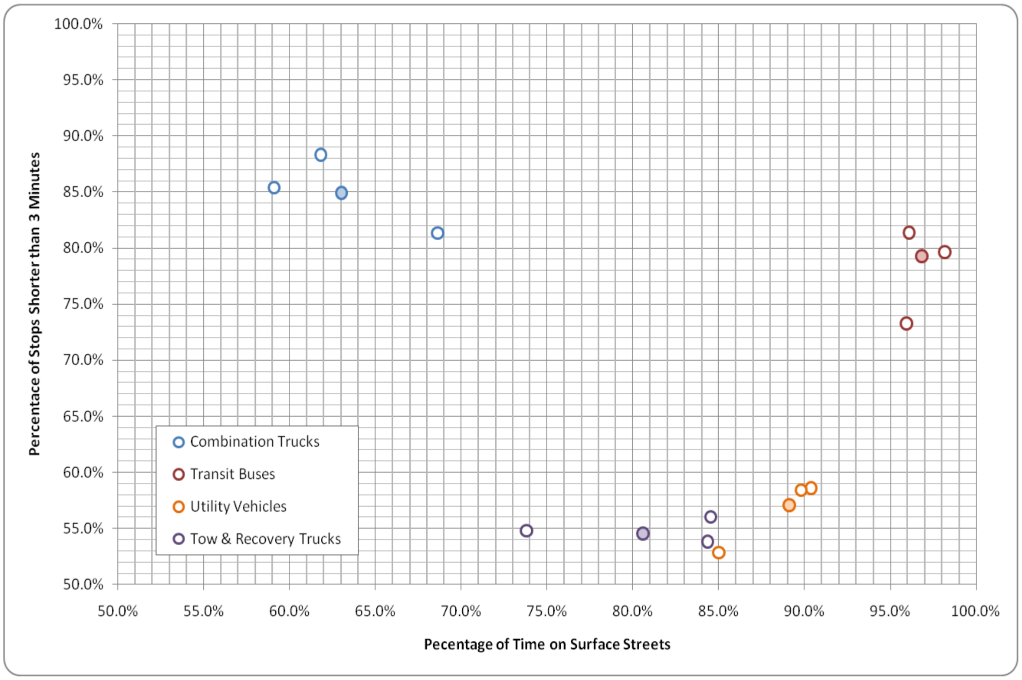

Figure 128. Percentage of stops shorter than 3 min by percentage of time on surface streets (MTDC vehicles 1 to 12).

5.6.2 Frequency of Stops

For each of the 12 participant vehicles, the stop data was clustered by day (i.e., midnight to 11:59 p.m.), and distributions of the number of daily stops for each vehicle in each vocation were created and are presented in 129 to 140. In each of these figures, the daily number of stops is grouped by two (i.e., one or two daily stops, three or four daily stops, and so on, up to more than 30 daily stops), and for each group, its percentage with respect to the total number of daily stops is presented. In all of the cases, only stops that lasted 30 s or more (i.e., the vehicle was stationary for 30 s or more) were considered.

The figures show that, as expected, there is variation among the different vocations studied. However, within a given vocation there is a certain degree of uniformity in the distribution of the number of daily stops. For the combination trucks (MTDC vehicles 1 to 3), there were slight differences in the distribution of the daily number of stops, mostly due to the areas in which these vehicles made their deliveries. For example, for the combination truck or regional delivery vocation, MTDC vehicle 2 functioned most of the time in urban areas, thereby having a higher probability of being stopped at a traffic light. For the other two vehicles in this vocation, there was a higher proportion of deliveries that required following rural routes. This resulted in vehicles 1 and 3 having very similar distributions, slightly different from that of vehicle 2; the latter showed a higher likelihood of having a higher number of daily stops than the other two (e.g., a 9.8% probability of observing more than 29 stops in one day for vehicle 2 vs. about a 2% probability for the other two vehicles).

The transit vehicles also presented similar distributions of daily stops among the three participating vehicles. However, because of the particular operations of transit buses, these distributions were very different from the distributions of the other three vocations. For example, the buses showed a probability of having more than 30 stops in a given day, much more than any of the other vocations; the towing and recovery vehicles were in second place. The transit buses also had the highest probability among all of the vehicles studied of presenting a very low number of daily stops. This was mostly because the buses spent a large amount of time idling at their garage or at the shop being repaired (see Chapter 4 for a description of the operations of the transit buses).

Utility vehicles 2 and 3 (MTDC vehicles 8 and 9) showed similar distributions, but these distributions were different from that presented by MTDC vehicle 7. This was because vehicles 8 and 9, which were very similar to one another, performed the same type of operation, which was slightly different from that of vehicle 7.

The three towing and recovery trucks had very similar distributions of daily stops. Similar to the transit vehicles, they showed a high probability of having more than 30 daily stops (17% to 25% for the towing and recovery vehicles vs. 28% to 40% for the transit buses).

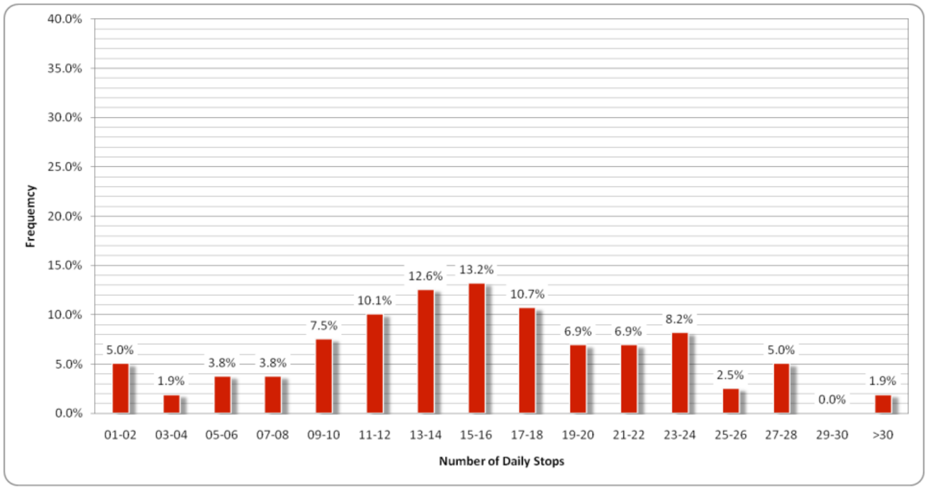

Figure 129. Combination truck 1 (MTDC vehicle 1) distribution of daily stops.

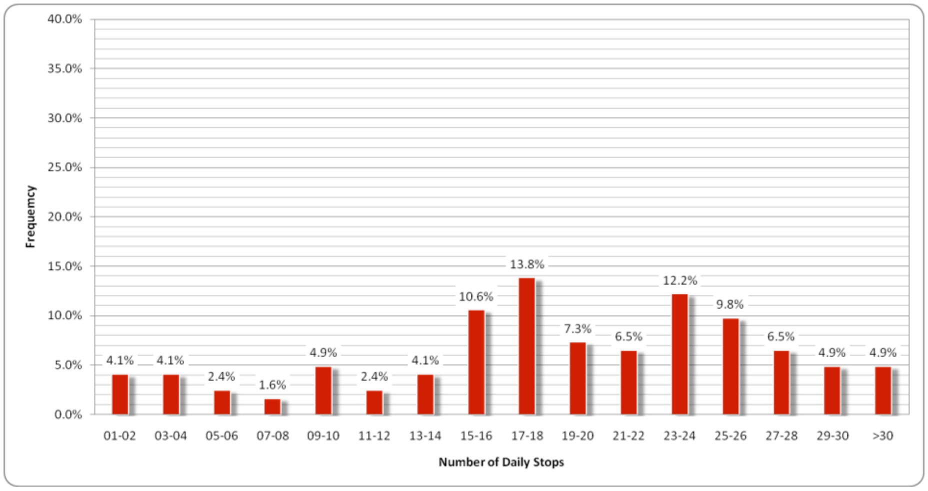

Figure 130. Combination truck 2 (MTDC vehicle 2) distribution of daily stops.

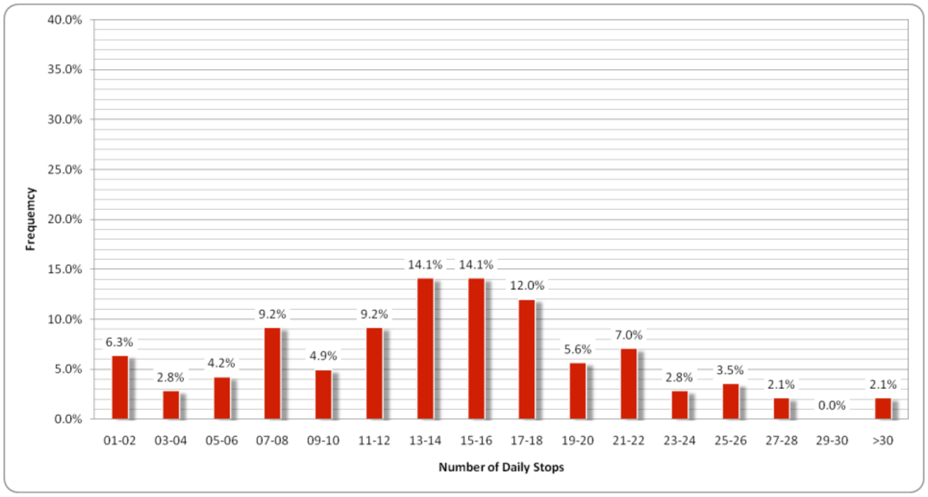

Figure 131. Combination truck 3 (MTDC vehicle 3) distribution of daily stops.

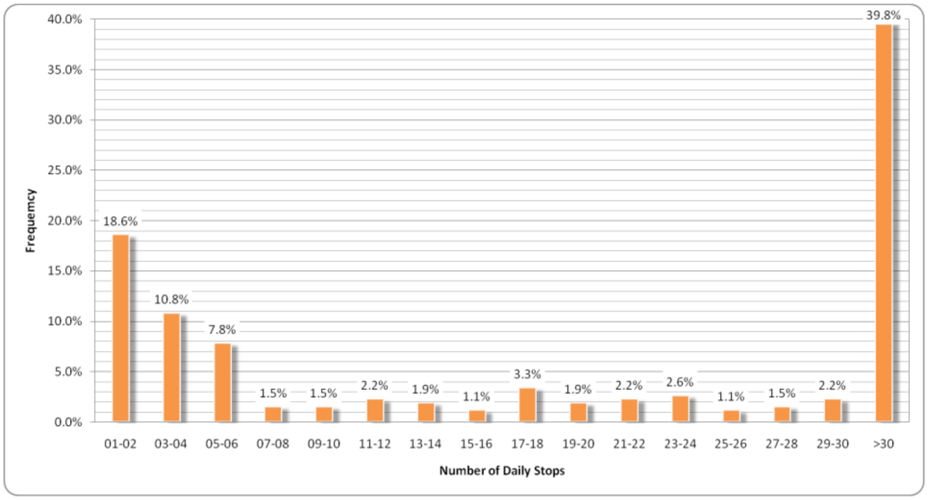

Figure 132. Transit bus 1 (MTDC vehicle 4) distribution of daily stops.

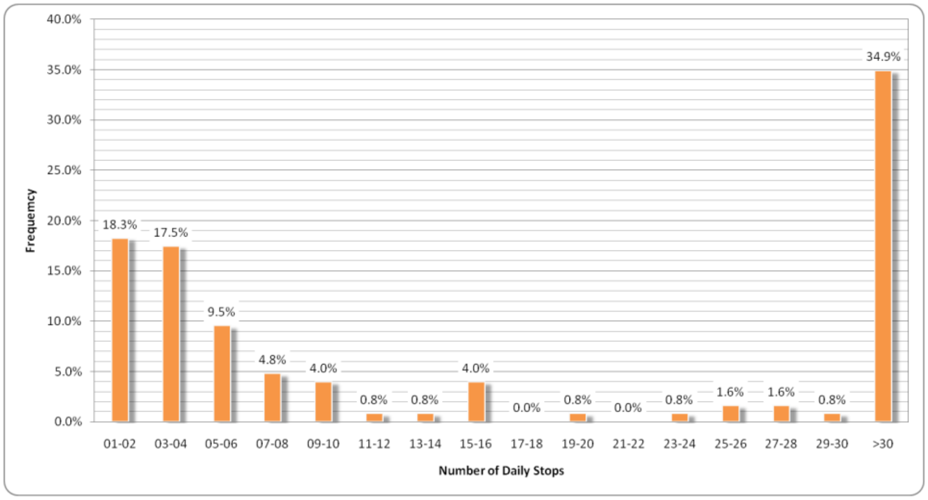

Figure 133. Transit bus 2 (MTDC vehicle 5) distribution of daily stops.

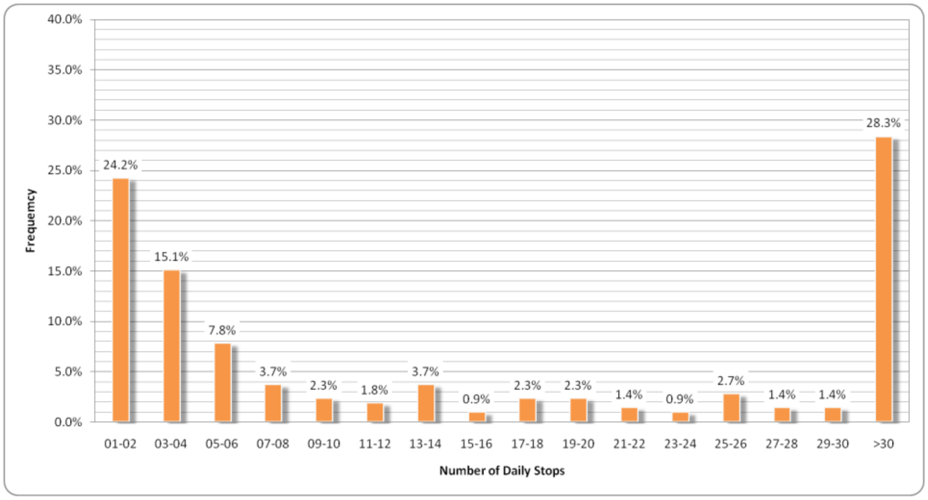

Figure 134. Transit bus 3 (MTDC vehicle 6) distribution of daily stops.

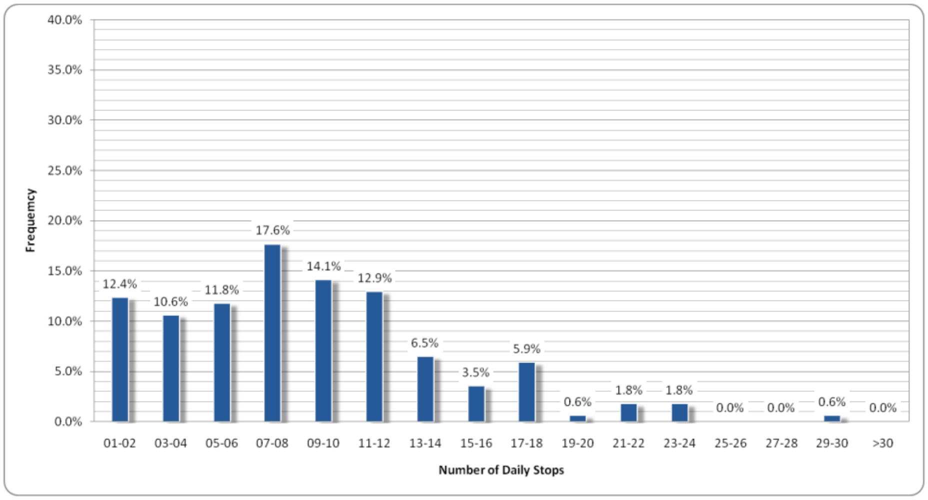

Figure 135. Utility vehicle 1 (MTDC vehicle 7) distribution of daily stops.

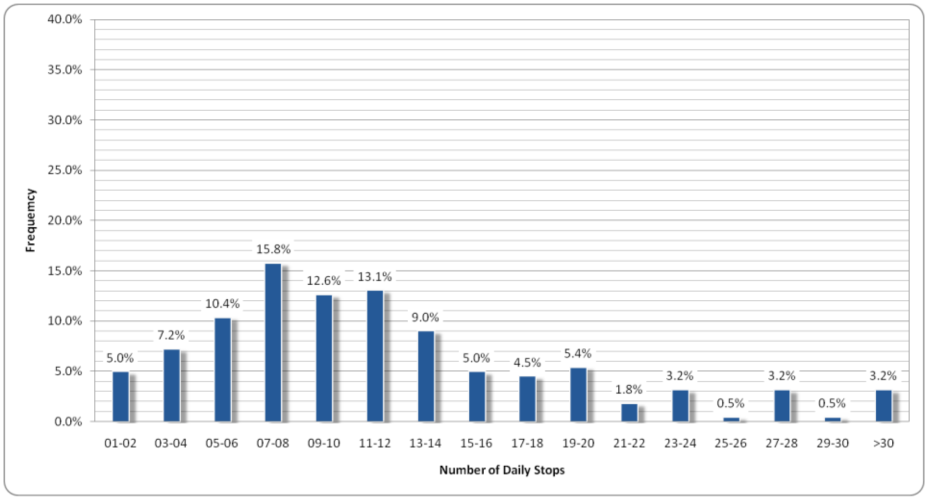

Figure 136. Utility vehicle 2 (MTDC vehicle 8) distribution of daily stops.

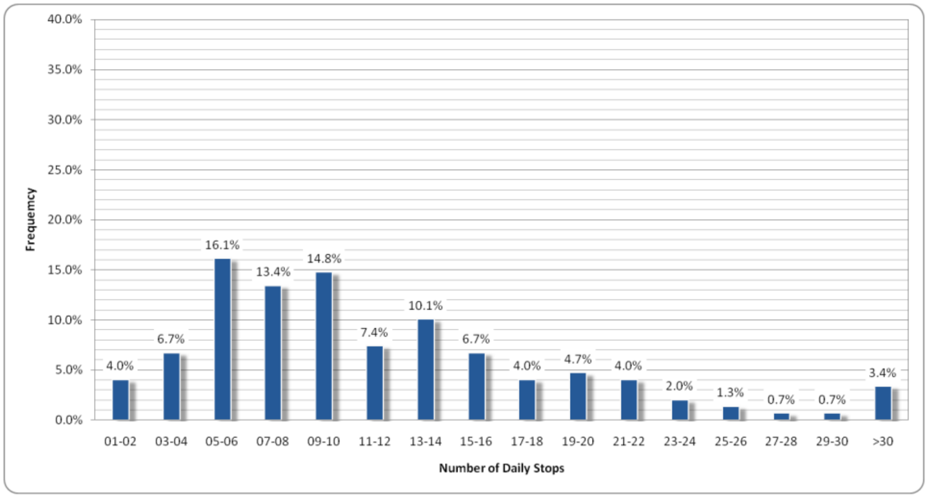

Figure 137. Utility vehicle 3 (MTDC vehicle 9) distribution of daily stops.

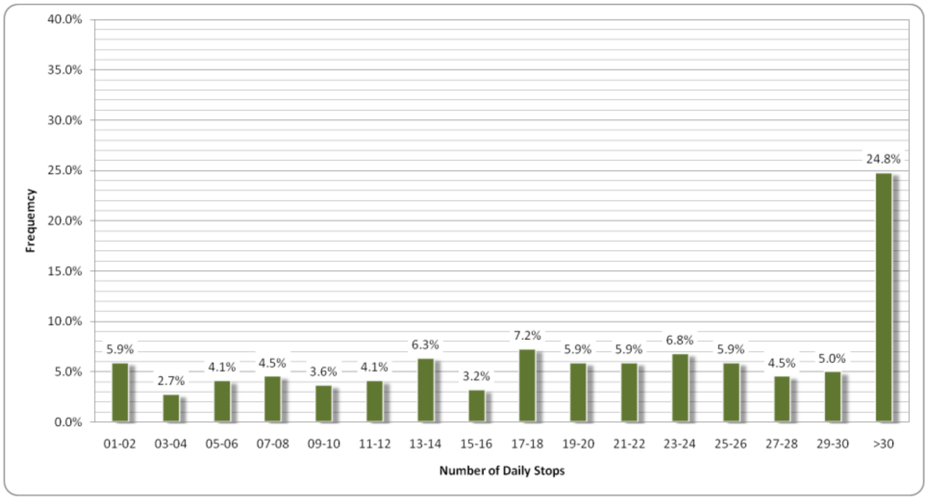

Figure 138. Towing and recovery truck 1 (MTDC vehicle 10) distribution of daily stops.

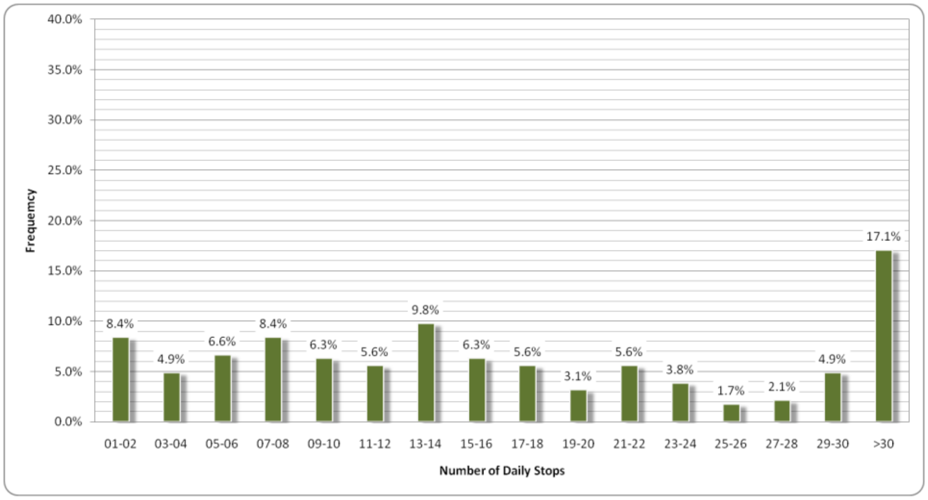

Figure 139. Towing and recovery truck 2 (MTDC vehicle 11) distribution of daily stops.

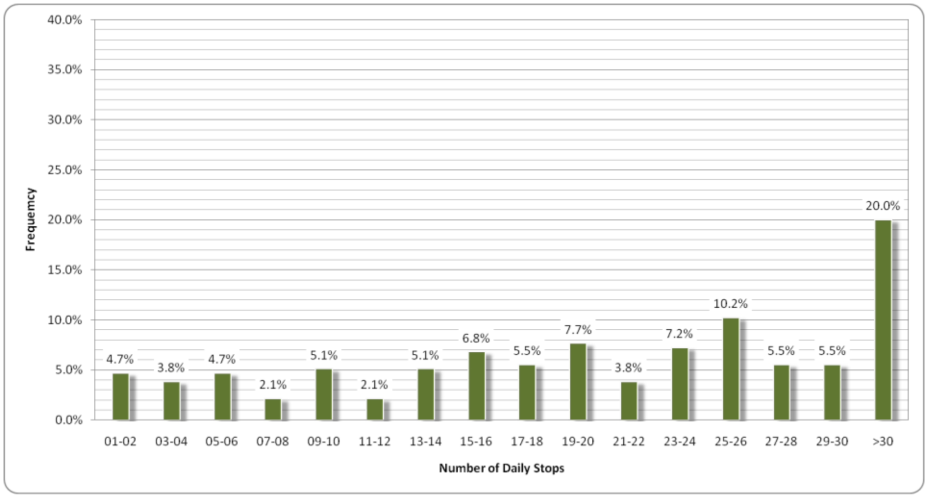

Figure 140. Towing and recovery truck 3 (MTDC vehicle 12) distribution of daily stops.

5.6.3 Length of Stops

The length of the stops was also analyzed and associated distributions were generated. Those distributions are presented in 141 to 152 for all of the 12 MTDC vehicles. In each figure, the abscissa shows the length of the stop (with engine running), for intervals measured in minutes, starting with stops that were less than 1 min in length (and longer than 30 s), followed by 1 min intervals until the 4–5 min long stop interval. Subsequent to this, the intervals have a length of 5 min, with the last interval presented being for stops with a duration ranging from 55 to 60 min. The ordinate shows the percentage of the total observations in each length-of-stop interval.

The combination trucks and the transit buses show similar distributions of stop length, with the vast majority of stops being shorter than 5 min (see 141 to 146). The utility vehicles show distributions in which the probability of observing stops with durations of 15 min or longer are much higher than for any of the other vocations. Also, for this analysis, the distributions are truncated at the 55–60 min interval; while none of the other vocations show any significant probabilities of observing stops that are more than an hour in length, for the utility vehicles, these probabilities range from 5 to 8%.

The towing and recovery trucks presented the least variation in terms of the distribution of the stop-time lengths among the three participating vehicle types. For these vehicles, the most likely stop-time length (besides stops at traffic lights and other related traffic delays) was for intervals of 5 to 15 min. These covered about 25% of all the stop lengths, with stop lengths larger than 15 min observed only in about 4 to 5% of the cases.

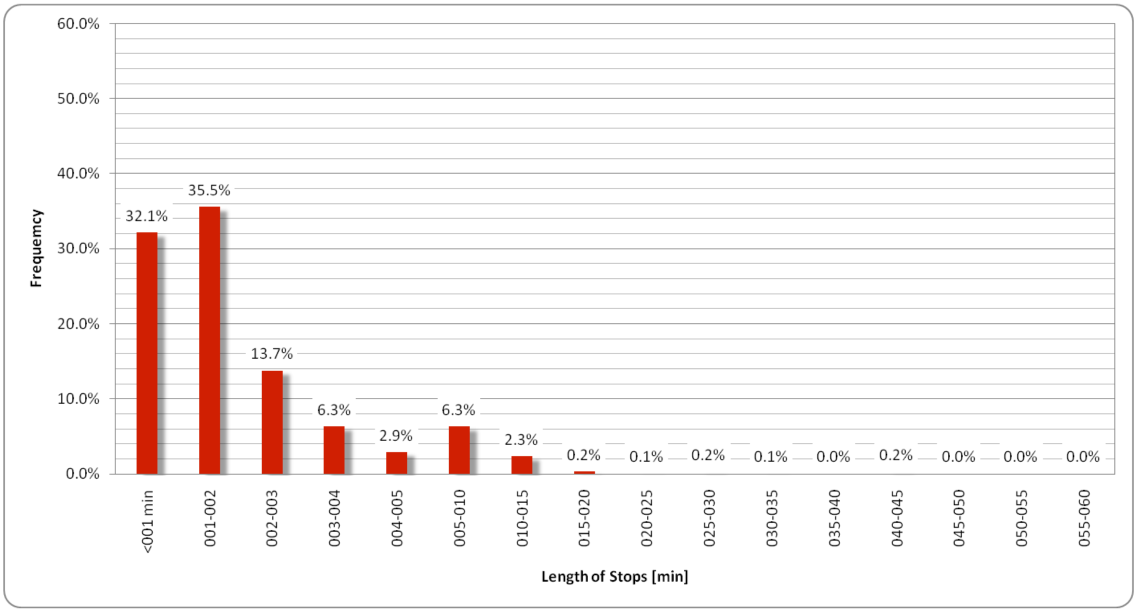

Figure 141. Combination truck 1 (MTDC vehicle 1) distribution of daily stop-time length.

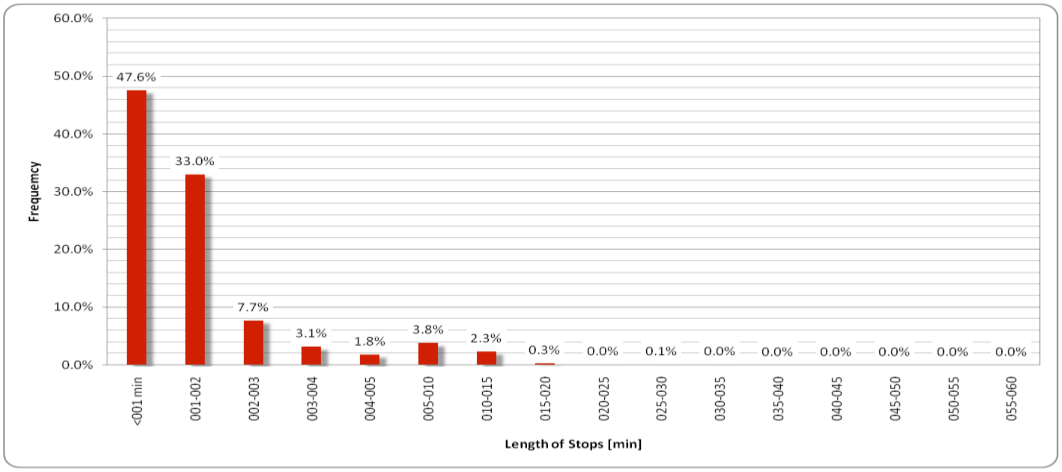

Figure 142. Combination truck 2 (MTDC vehicle 2) distribution of daily stop-time length.

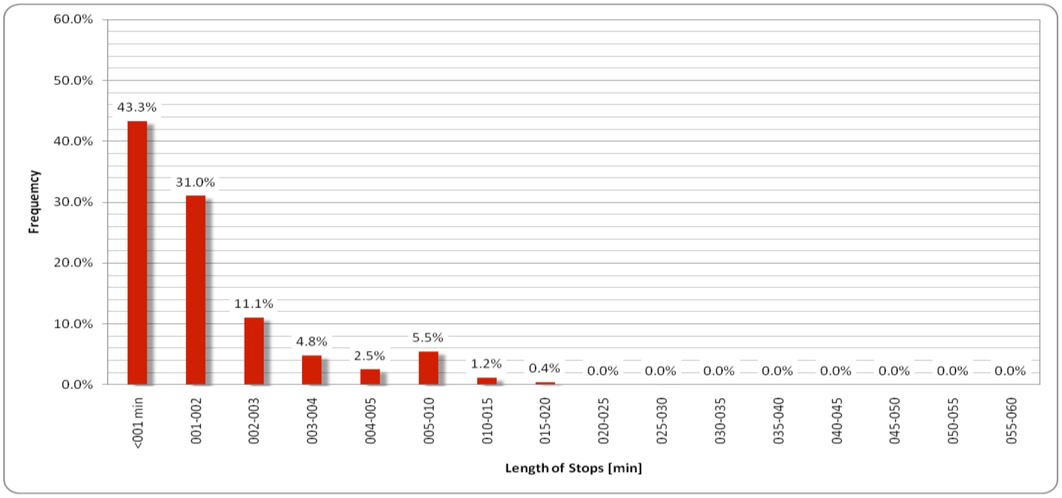

Figure 143. Combination truck 3 (MTDC vehicle 3) distribution of daily stop-time length.

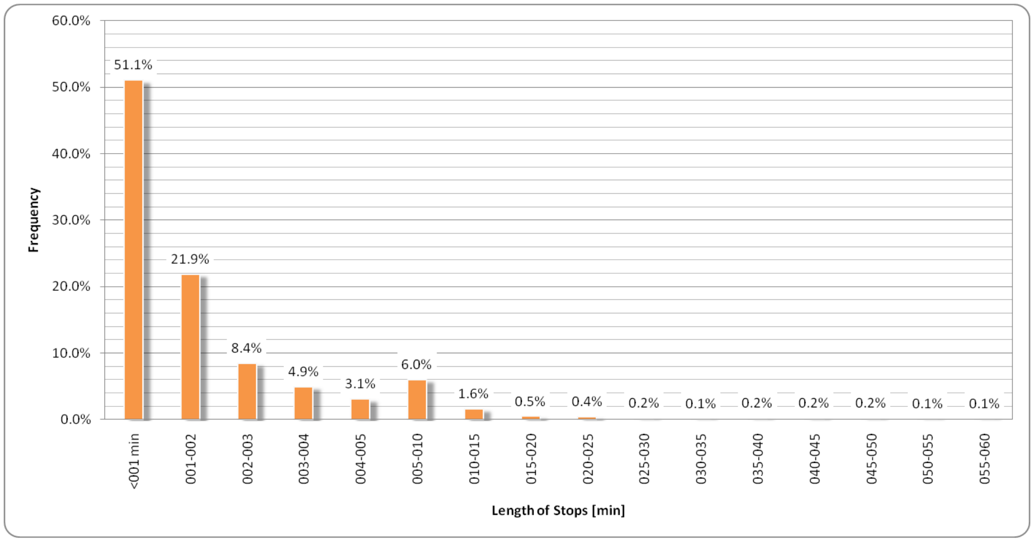

Figure 144. Transit bus 1 (MTDC vehicle 4) distribution of stop-time length.

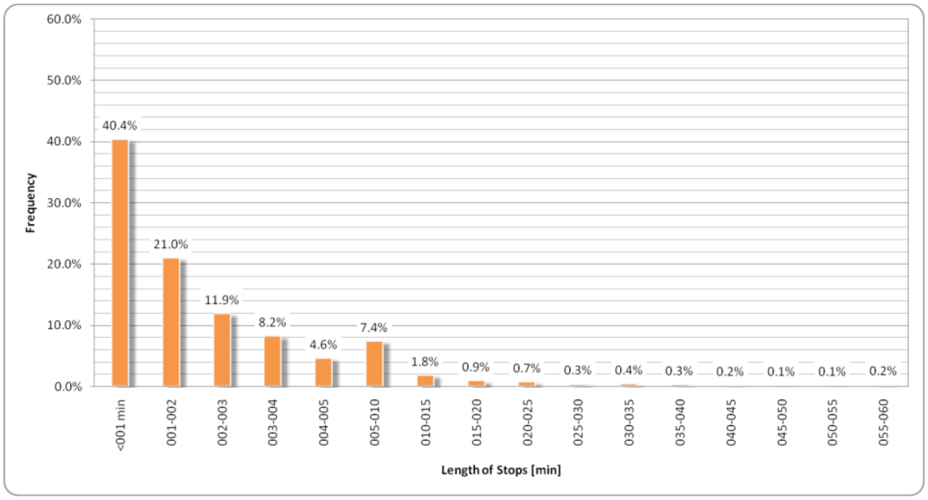

Figure 145. Transit bus 2 (MTDC vehicle 5) distribution of stop-time length.

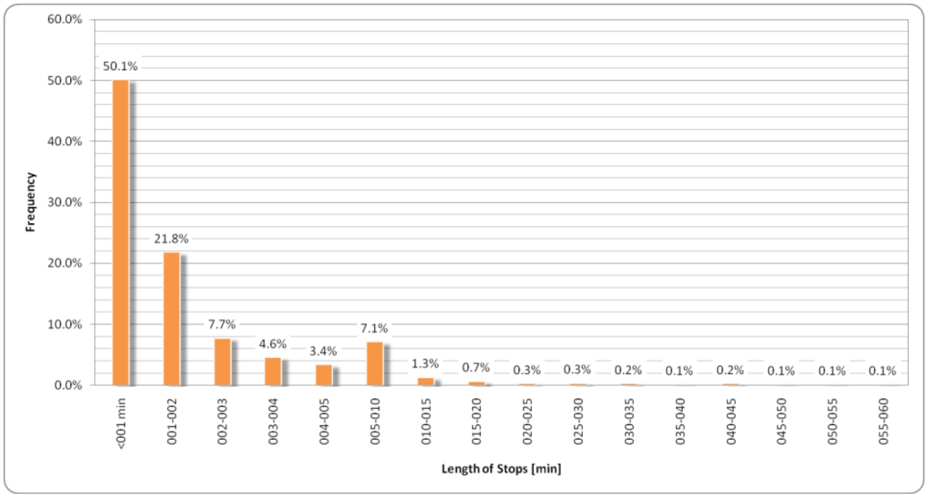

Figure 146. Transit bus 3 (MTDC vehicle 6) distribution of stop-time length.

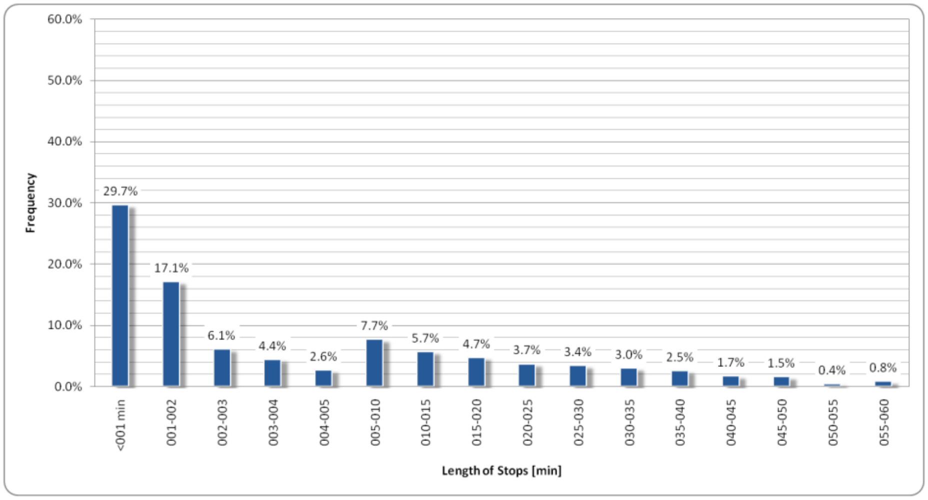

Figure 147. Utility vehicle 1 (MTDC vehicle 7) distribution of stop-time length.

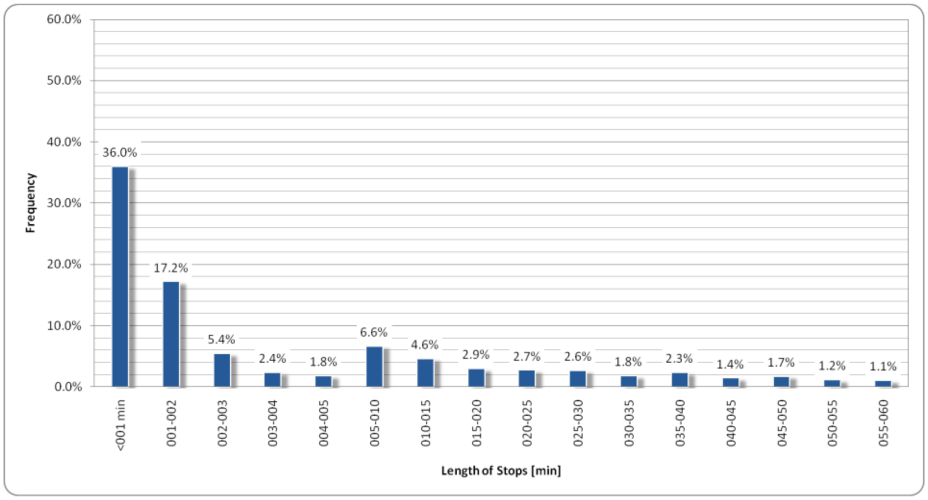

Figure 148. Utility vehicle 2 (MTDC vehicle 8) distribution of stop-time length.

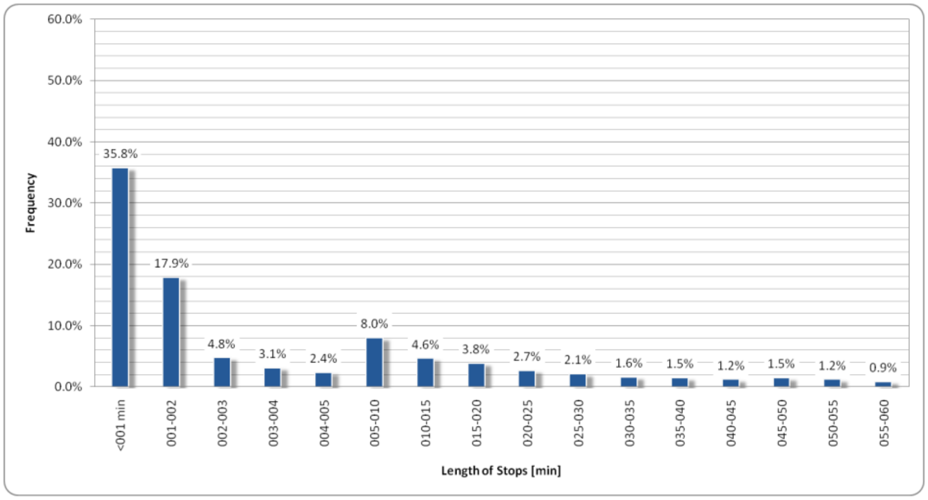

Figure 149. Utility vehicle 3 (MTDC vehicle 9) distribution of stop-time length.

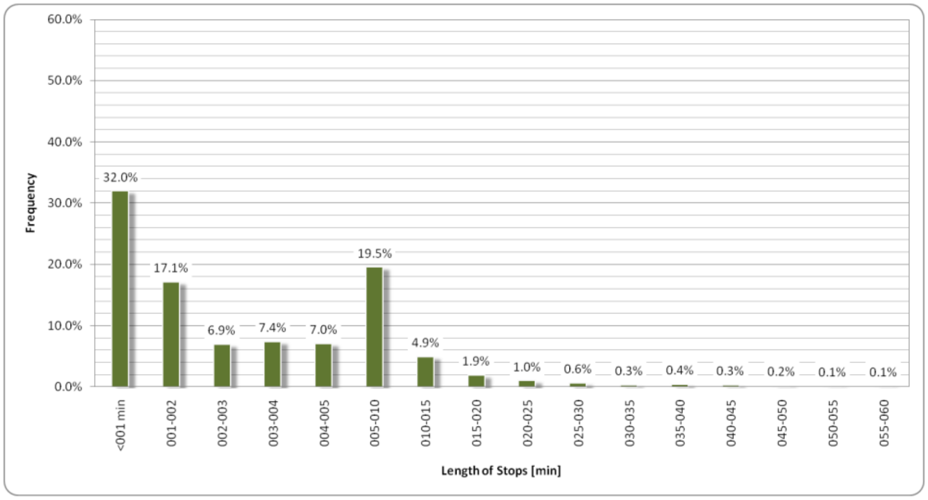

Figure 150. Towing and recovery truck 1 (MTDC vehicle 10) distribution of stop-time length.

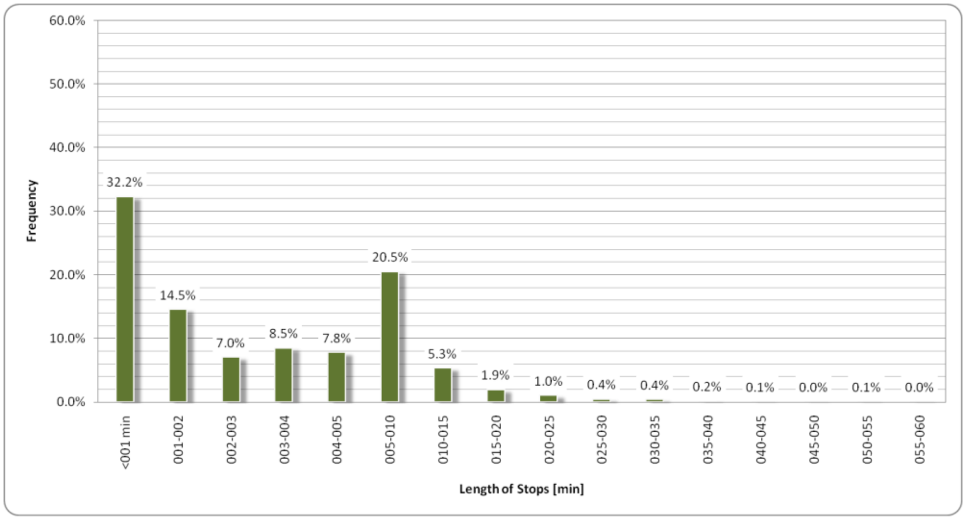

Figure 151. Towing and recovery truck 2 (MTDC vehicle 11) distribution of stop-time length.

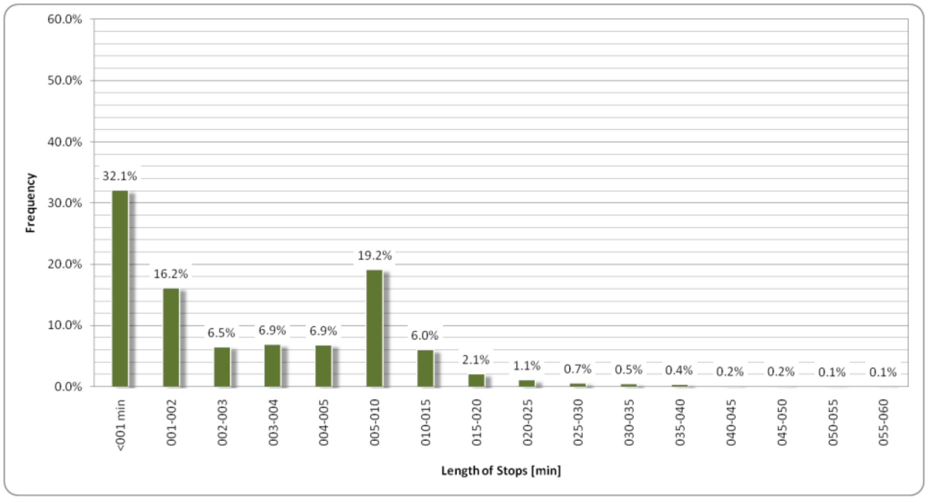

Figure 152. Towing and recovery truck 3 (MTDC vehicle 12) distribution of stop-time length.

6. LESSONS LEARNED

The lessons learned in the Part 1 MTDC FOT data collection and analysis period were varied. Some lessons learned involved improvements over the previous HTDC effort. Others were immediately incorporated into the testing protocols being employed at the time and allowed for more productive and efficient research and data collection. An additional category of lessons learned were of a nature that did not allow for more immediate or short-term adoption during the Part 1 FOT but could be addressed in the Part 2 MTDC FOT or other future research.

6.1 IMPROVEMENTS FROM HTDC PRIOR TO THE PART 1 MTDC FOT

Several changes were made to the data collection methodology based on lessons learned from previous duty cycle work, such as that conducted within the HTDC project. Some improvements or lessons learned were not under the direct control of the project team but were a result of the nature of medium-truck operation for the vocations studied.

6.1.1 Modifications to Data Acquisition System

A key improvement to the DASs for the Part 1 MTDC FOT was the inclusion of a cellular modem to facilitate remote data transfers. Upon implementation of this approach, a number of additional benefits became apparent. Not only did this additional equipment make possible the automated retrieval of data from the test vehicles (greatly reducing the need for research staff to be involved in the day-to-day FOT operation), but also it allowed the retrieval to be done more frequently (daily rather than every few weeks). Because the data retrieval software was integrated with an ORNL-developed automated error-checking routine, much quicker error detection and response was possible.

Because of the problems involved in the repurposing of the weather stations for vehicle use, as was done in the HTDC work, no weather station was installed on the test vehicles. Instead, ORNL worked with technicians at the partners' respective shops to make a connection to the vehicle's wipers. This allowed basic weather information regarding precipitation to be collected without the installation of any additional equipment. In addition, temperature measurements were read from the test vehicle's data bus where available.

The DAS wiring was improved to streamline its installation,. Bulkhead connectors were installed in the DAS case to make possible the separate installation of the cabling. The mating connectors were incorporated into pre-made cabling, which was given to the partners for installation by their technicians.

6.1.2 Coordination with Fleet Partners

One problem occasionally encountered in the HTDC FOT was the limited availability of the test vehicles for data download and correction of minor sensor problems. Medium truck operations typically run on a more predictable schedule, making the scheduling of visits to correct equipment easier. In addition, ORNL was able to interface with a main point of contact in each of the partners' shops to check on equipment and coordinate visits. This led to reduced downtime and reduced loss of data in the event of easily corrected sensor problems. In addition, ORNL partnered with fleets in the local area rather than those that were more than an hour away, as was the case in the HTDC efforts; this greatly reduced staff travel time when such visits were needed.

In the HTDC project, both tractors and trailers were instrumented with the Air-Weigh self-weighing unit. Although the fleet management indicated they would attempt to see that instrumented tractors and trailers were mated as often as possible, this proved impractical for their drop-and-hook operation. Consequently, only a small percentage of the data collected involved an instrumented trailer. Because the delivery fleet partner (HTH) in the MTDC data collection effort used a drop-and-hook operation, a decision was made not to direct resources toward the instrumentation of any trailers because of the small amount of additional data that would be available in their operation.

As a result of the lessons learned from the HTDC, ORNL was able to work more efficiently with the fleet partners, with minimal departure from their standard operating procedures. For example, ORNL discussed standard procedures with fleets prior to instrumentation of the test vehicles to prevent damage to the GPS antennas due to pressure-washing. Certified weight information was obtained by coordinating planned trips to inspection stations to obtain weigh tickets for the weight estimation model. In addition, rather than attempting long-term collection of fuel tickets for calibration of the fuel model (which proved unsuccessful in the HTDC efforts), a short-term study was performed with driver incentives for participation during the one-month study period. This methodology proved successful, providing the necessary data with a high degree of accuracy.

6.2 IMPROVEMENTS DURING THE PART 1 MTDC FOT

In order for the data to be retrieved remotely, the DAS had to be powered up; thus, for this remote upload to take place on a regular basis, the DAS had to be left on at all times. However, as a result, the vehicles' batteries were frequently drained. To correct this problem, digital timers were installed to "wake" the system at scheduled data upload times during the night for data retrieval and to ensure that the systems were on at a predetermined time during the day in the event of the occasional problem with the automated process requiring human intervention. This solution proved successful both in eliminating the battery problems for the fleet partner and in making the vehicles available for remote access.

Toward the beginning of the Part 1 MTDC FOT, the combination vehicles were experiencing problems resulting from an unavoidable drop in voltage when the engine started. A capacitor was installed to provide a more constant voltage during the brief startup period, as recommended by the fleet partner's shop manager. This solution proved successful; and although this problem had not yet been encountered on all of the vehicles, capacitors were also installed in the remainder of the DASs as a preventative measure.

6.3 IMPROVEMENTS PRIOR TO PART 2 OF THE MTDC EFFORT

Although the method of making vehicle connections in Part1 1 of the MTDC FOT was a significant improvement over that used in HTDC, the partner technicians frequently had to make several different connections to a few contact points to accommodate the additional sensors installed. As a result, wires would occasionally become disconnected and have to be replaced. To correct this problem, a single DASIB was constructed for each vehicle. This allowed a single connection to be made to each key point in the vehicle (e.g., data bus, power). Mating connectors were made so that additional sensors could interface to the DASIB, which were configured as necessary to accommodate different types of sensors. In addition to making the installation less cumbersome, the use of the DASIB minimized connection-related problems during the Part 2 FOT.

In Part 1 of the MTDC FOT, technical difficulties were encountered with the VBOX GPS unit, particularly with the combination vehicles. Because systems were unable to maintain satellite lock for long periods of time, the units frequently had to be manually reset or "cold started," approximately once every few weeks. Because the channels were checked each time the data was uploaded, this problem was identified and corrected soon after it occurred, resulting in a minimal loss of data. Corrective actions included replacing the GPS antenna, ensuring that the units were not subjected to frequent power cycles, and ultimately returning the units to the manufacturer for repair. When these measures failed to determine the cause of the problem, the decision was made to explore other 5 Hz GPS solutions compatible with the eDAQ-lite. At about the same time, HBM, the manufacturer of the eDAQ-lite, began producing a hardware layer with a built-in GPS of the needed resolution. This layer was tested with the DASs, found to be comparable to the VBOX, and installed in all of the DASs for the Part 2 MTDC FOT in lieu of the VBOX units.

6.4 ADDITIONAL LESSONS LEARNED

During the FOT, some issues were not identified until after the FOT was completed, or could not be corrected because of resource limitations; future research should seek to avoid such issues. In some instances, approaches used in the MTDC effort resulted in positive outcomes and are therefore recommended for similar data collection efforts. This research also brought to light general issues inherent in data collection efforts of the type and magnitude of the MTDC program which can inform future research programs.

6.4.1 General Data Collection Methodology

During the Part 1 MTDC FOT, most of the equipment functioned as expected. Preliminary testing of each DAS allowed most of the problems to be discovered and resolved before initiation of the FOT. The problems which were not foreseen during the early stages of the testing involved the long-term nature of the project; these could not be practically simulated prior to the start of the FOT.

The complexity of the DAS meant that equipment issues typically resulted in slightly longer delays because these problems were corrected in accordance with standard procedures characteristic of a national laboratory (e.g., the requirement for working through telecommunications and/or procurement departments). Although the budget for this project did not support the purchase of a complete spare DAS in the event of failures, the construction of a spare may prove cost-effective for future projects in which unanticipated delays of 1–6 weeks are unacceptable.

6.4.2 Use of Safety Sensors

The downtime for the fleet vehicles required to install the safety sensors was longer than expected, inconveniencing the partners and impacting fleet operations. Although the partners were willing to accommodate by continuing to allow the sensor technicians to use their shop and rearranging their delivery schedules, future installations should be better understood to minimize the impact to the partners. Even without safety sensors, installing the DAS is time- and labor-intensive because of the complexity of the system. While the depth of data and additional capabilities (such as remote data retrieval) make the effort worthwhile, consideration should be given to cost- and time-saving strategies that minimize the impact to the operations of partnering fleets.

The particular TPMS selected for this effort proved problematic in some instances. Personnel from the partnering fleet reported false alarms and the occasional unresponsive sensor. Additionally, the values reported on the data bus were found to not always agree with the in-cab display. If time and budget permit, future projects in which this technology will be used should include a test period to determine whether the system will be sufficiently robust for long-term data collection.

Unlike previous research, the Part 2 MTDC FOT involved strain-gauge–based self-weighing systems for two of the towing and recovery vehicles. Because of safety and warranty concerns, the strain gauges were attached to the instrumented axles with epoxy rather than being welded on. Within the first few weeks of the FOT, both strain-gauge systems had failed. If future research involves this technology or other sensors or equipment not previously used in long-term data collection, it is suggested that the equipment be tested on a single vehicle for 1–2 months to ensure it is sufficiently robust before investing the time and effort on instrumenting other vehicles.

The third and final Part 2 FOT vehicle (MTDC vehicle 12) was equipped with a self-weighing system that involved air-suspension–based technology (like that used in the HTDC FOT and the Part 1 MTDC FOT). However, unlike in previous efforts, the data required extensive post-processing to be useable. Because only a limited and cursory analysis could be performed during the FOT—the analysis task being scheduled for after the completion of the FOT—the extent of the data corruption in the collected data was not evident until after all of the data had been collected. It is recommended that, to identify and correct such problems in the future, the project tasks and budget be arranged to place the bulk of the data analysis efforts toward the beginning of the data collection. This will allow all of the data cleaning, processing, and analysis software to be written at the beginning of the FOT so that data analysis can be performed at regular intervals as the data comes in (perhaps monthly). As with any analyses, researchers should directly observe the results rather than rely primarily on the software to flag unexpected data. To interpret the data and identify inconsistencies, close cooperation with personnel from both carriers and sensor companies should be maintained throughout the analysis task.

6.4.3 Test Vehicle Selection

To collect duty cycles representing a variety of vehicle types from the utility vocation, lower classes of medium trucks were originally assessed for inclusion in the FOT. These lighter medium trucks were found to have OBDII data buses, a type of CAN data bus similar to J1939 with messages that can be read with only minor adjustments to the available DAS. However, testing of two different OBDII trucks revealed that while a standard data set of duty cycle information does exist for OBDII, it was not reliably adopted by industry in the same way that the parallel J1939/71 standard was adopted. Consequently, although the raw data bus messages could be read by the DAS, the inability to reliably interpret the crucial signals related to duty cycle collection (e.g., vehicle speed, engine speed, torque) made the inclusion of these lighter vehicles impossible. This experience points to the need for a partnership with a vehicle manufacturer in any future collection of data from OBDII vehicles; without a prior commitment from a manufacturer to provide the needed OBDII information, the risks associated with such an effort would be untenable.

The decision was made to instrument three vehicles from each vocation; this proved to be a good minimum number of test vehicles in the absence of spare DASs. One of the towing and recovery vehicles was not used as much as anticipated because of driver health, and another vehicle’s DAS had occasional equipment and communication issues. Since three vehicles were instrumented, a full set of data was still collected to represent the duty cycle of that vocation; however, these events point to the need for a minimum of three vehicles to be instrumented in order to minimize the risk of data loss. Multiple test vehicles also allowed the capture of some variation in the data within each vocation.

7. SUMMARY OF RESULTS AND CONCLUSIONS

In the MTDC project, 12 vehicles were instrumented: three Class-7 tractors from the HTH fleet, three Class-7 KAT buses, three Class-8 KUB vehicles (one derrick and two bucket trucks), and three Class-6 towing and recovery trucks. Over the length of the data collection effort (approximately 28 months for Part 1 and 2 of the MTDC FOTs combined), more than 70 channels of data were collected at a rate of 5 Hz. The data gathered in this project included information such as instantaneous fuel rate, engine speed, gear ratio, vehicle speed, and other information read from the vehicle's data bus; and spatial information (e.g., latitude, longitude, and altitude) acquired from a GPS device. Additional devices were mounted on 9 of the 12 participating vehicles to collect weight information. These devices were mounted on the tractors of the three combination trucks, the buses, and the towing and recovery trucks. Seven of these devices were air suspension sensor devices, and the other two, which were mounted on two of the towing and recovery trucks, were strain-gage–based devices. Some of the vehicles were also mounted with safety sensors providing brake and tire information in partnership with FMCSA, yielding valuable information to support related research efforts.

During the 1 year data collection period for the Part 1 MTDC FOT, the six participating vehicles logged over 105,000 miles (45,400 for the combination trucks and 59,400 for the transit buses) and consumed over 17,000 gal of fuel (6,000 for the combination trucks and 11,300 for the transit buses) while conducting business in the East Tennessee area. In Part 2 of the MTDC FOT, the utility vehicles and towing and recovery trucks traveled 88,000 miles (18,000 miles for former and 70,000 for the latter), and consumed 13,000 gal of fuel (5,000 and 8,000, for the utility vehicles and towing and recovery trucks, respectively). Use of the test vehicles, and costs related to the fuel, drivers' time, insurance, and the use of fleet partners' facilities for vehicle instrumentation and DAS maintenance were provided gratis to this project. In addition, the data gathered from the FMCSA brake and tire systems (in Part 1 of the MTDC FOT) was available to ORNL and DOE at no additional cost. These partnerships represent a significant cost savings to DOE and made possible the collection of a richer set of real-world–based operational data for medium trucks.

For the combination trucks, the largest proportion of idling time (63%) and fuel consumed while idling (59%) correspond to idling intervals that lasted for 0–5 min (i.e., traffic congestion and delay at traffic signals). This is followed by intervals of 5–15 min of idling time (25% of the total time and 28% of the total fuel consumed while idling), and by the 15–60 min time interval. The latter involves mostly idling while being stopped for deliveries. The 120–180 min interval is due to the vehicles being maintained or repaired at the company's garage (9.6 h over a period of 1 year for the three vehicles). The transit buses also spent most of their idling time (35%) in congestion and bus dwell stops (0–5 min idling interval) ,which also consumed the largest proportion of fuel spent while idling. However, as opposed to the combination trucks, the transit buses spent 22% of their idling time in intervals that are longer than 4 h, also consuming about 21% of the fuel spent while idling. These long idling times were observed mostly at the parking lot while the vehicles were waiting to start a trip and are currently being addressed by KAT to reduce fuel usage.

In the case of the utility vehicles, the largest proportion of idling time (38%) and fuel consumed while idling (40%) correspond to idling intervals of 15–60 min, followed by the 60–120 min interval (24% of the total idling time and 23% of the total fuel consumption while idling), and the 2–3 h interval, all corresponding to the vehicle being parked and idling (to allow PTO operation) while maintaining and repairing electric power lines. Delays at traffic lights and delays due to congestion (i.e., the 0–5 min interval) ranked fourth in terms of idling time and idling fuel consumed, 9% and 8%, respectively. For the towing and recovery trucks, the largest percentage of idling time and fuel consumed while idling (40% and 41%, respectively) corresponded to the 5–15 min interval. The 15–60 min interval ranked third with

25% of the total idling time and 22% of the total idling fuel consumed. These two intervals (i.e., the 5–15 min and 15–60 min intervals) mostly correspond to the loading and unloading of the towed vehicles. Delays at traffic light and delays due to congestion accounted for the second largest time and fuel consumed percentages while idling (31% for both measures). Idling for more than 2 h was negligible in the case of the towing and recovery trucks.

Before using the fuel data available from the data bus, a short-term study was performed to ensure that the source of this information provided an accurate representation of fuel usage. After that study was conducted (with the results showing a high accuracy in the fuel information provided by the vehicle data bus), the data collected in the project was used to compute the overall FEs, that is, the FEs computed by taking into consideration idling times as well as moving FEs (i.e., fuel consumed only when the vehicle was moving) of combination trucks and transit buses. The utility vehicles, because the way they were operated, presented the largest percentage difference between moving and overall FEs—between 15 and 20 times higher than the difference for the combination trucks (i.e., the vehicles with the lowest percentage difference between overall and moving FEs).

One very important variable affecting the FE of any vehicle is its payload level. Based on vehicle weight data collected at commercial scales (i.e., Inspection Stations in Knox County), ORNL developed a model that predicted the trailer weight based on the tractor weight as provided by the Air-Weigh device. This model was used to assign trailer weight to each one of the records in the database of information collected in this project. For the transit buses, the deployed Air-Weigh devices provided weight information for the entire vehicle; therefore, it was not necessary to develop a payload estimation model in this case. In the case of the towing and recovery trucks, ORNL used calibration weight information collected for that vehicle by the THP to make corrections to the collected weight information because of a data-drifting phenomenon (only the truck mounted with an air suspension weigh sensor provided sensible data; for the other two test vehicles in this vocation, the strain gage sensors lasted only a fraction of the duration of the FOT). The utility vehicles were not instrumented with weight sensors since they do not experience significant variations in weight while performing their vocational activities.

For both the combination trucks and the towing and recovery trucks, vehicle weight was divided into four categories. For the combination trucks, these categories were (1) tractor with empty trailer, (2) light load (total vehicle weight between 23,000 and 26,999 lb), (3) medium load (total vehicle weight between 27,000 and 31,999 lb), and (4) heavy load (total vehicle weight above 32,000 lb). For the towing and recovery trucks, the categories were (1) empty vehicle (total vehicle weight less than 18,500 lb), (2) light load (total vehicle weight between 18,500 and 22,499 lb), (3) medium load (total vehicle weight between 22,500 and 25,499 lb), and (4) heavy load (total vehicle weight above 25,500 lb). In the case of the transit buses, the vehicle weight was divided into three categories (1) empty bus (total vehicle weight less than 22,500 lb), (2) light fare (total vehicle weight between 22,500 and 25,499 lb), and (3) heavy fare (total vehicle weight above 25,500 lb).

On average, the combination trucks weighed between 27,700 and 29,000 lb, the buses weighed between 23,000 and 23,800 lb, and the towing and recovery trucks weighed about 19,900 lb. Very few trips with a tractor and empty trailer were observed. Most of the trips for MTDC vehicle 2 (98%) were at a light or medium load; for MTDC vehicle 3, almost 70% of the trips were at the medium and high level loads. Transit buses 2 and 3 (MTDC vehicles 5 and 6) operated almost 90% of the time with a light fare. Transit bus 3 had the largest average weight, indicating that this was the vehicle that carried the largest number of passengers (on average). Transit bus 1 (i.e., MTDC vehicle 4), on the other hand, spent almost 30% of the time at an empty level. This was mostly due to idling at the parking garage. Transit bus 1 (MTDC vehicle 4) had the lowest overall FE of the three buses.

To generate the distribution of FEs under the payload levels described, 10-mile segments were considered for which the FE was computed and counted as one observation. Overall, as expected, the FE decreased as the payload increased for the combination trucks. However, because the payload categories are relatively narrow and low, the variation of the FE is not significant (the combination trucks never made any trips that were above 42,000 lb, which is below the legal weight limit for Class-7 combination trucks). The same was observed for the towing and recovery trucks. In the case of the transit buses, the relationship between FE and vehicle weight is not as would be predicted (i.e., decreasing FE with increasing payload). This is due to several factors. First, when the vehicle is empty (i.e., the lowest payload), it spends a considerable amount of time idling. This results in very low FEs for this load level. At the other end of the spectrum, the highway routes (i.e., express routes) are the ones that carry the largest number of passengers. The buses on these routes spent very little dwell time (there are fewer bus stops) and encounter the least number of traffic lights. The result is FEs that are higher than regular surface-street routes (light fare) that have many more stops (bus stops and traffic signals).

The data collected in this project was also used to investigate two aspects of routing: (1) the variability that may exist in duty cycles generated by the same vocation and following the same route and (2) the effect of route optimization on fuel savings.

To study duty cycle variability, two sets of data gathered from the transit buses were identified. A 19-km segment of Westbound I-40 in Knoxville, Tennessee, was selected and the corresponding duty cycles were extracted from the database. The duration of the 74 highway duty cycles ranged from 10.5 to 27.6 min with an average duration of 12.6 min and a standard deviation of 2.71 min. To analyze surface-street transit bus duty cycles, a 4.9 km loop in downtown Knoxville was selected and the corresponding duty cycles extracted from the database. Thirty-eight surface-street duty cycles with the characteristics described were selected. The duration of the duty cycles ranged from 10.9 to 22.8 min with an average duration of 18.4 min and a standard deviation of 3.29 min.

This variability of the duty cycles within a given category (i.e., freeway or surface-street) could be measured by the ratio of the standard deviation of the distribution of duty cycle duration over the mean of that distribution. For the 74 duty cycles, this ratio is 0.214 (i.e., 2.71 min/12.7 min). For the five top and five bottom duty cycles—ranked using the average speed of the duty cycle—the variability was computed at 0.06 and 0.357, respectively. When they were combined (i.e., in ten duty cycles), the variability increased to 0.402. In the same way, the 38 surface-street duty cycles had a ratio equal to 0.179 (i.e., 3.29 min/18.4 min). For the five top and five bottom duty cycles, the variability was computed at 0.134 and 0.262, respectively. When they were combined (i.e., in ten duty cycles), the variability increased to 0.308. Using this measure, the highway duty cycles presented a higher variability than the surface-street duty cycles.

To assess the effects of route and stop location optimization on fuel consumption, 31 trips were selected arbitrarily from the database of trips collected by the local delivery vocation trucks participating in the project. Stops that lasted more than 10 min were identified and mapped using inexpensive mapping and routing software. Three alternatives were analyzed: (1) the original routing and stop location sequence, (2) the original stop location sequence with route optimization), and (3) stop location sequence and route optimization. In most of the cases studied, alternative 2 gave better results than alternative 1 in all of the measures considered (including travel time and fuel savings). Alternative 3 always performed better than or similar to alternative 1 in terms of these measures.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 PROGRAMMATIC

8.1.1 Large-Scale Duty Cycle Data Collection

Wireless communication technologies over the past decade have made viable the possibility of collecting limited truck duty cycle data automatically and remotely with minor software changes to existing onboard telematics devices in use by the industry. Such technology would be of particular value in considering a large-scale collection of limited duty cycle data. This method would permit the collection of data from across the country without requiring researchers to physically interact with the test vehicles, provided the partnering fleet vehicles are equipped with the needed technology. Prior to such data collection efforts, a determination should be made as to the minimum data set necessary to significantly enhance research to support FE, safety, and emissions research; provide insights to vehicle manufacturers regarding design of vehicles based on user experiences; and provide the trucking industry with information that could be used to make their operations more fuel- and cost-efficient. The data collected in the MTDC and HTDC efforts could be used to support this initial investigation Through the collection of even very limited duty cycle data/(velocity, acceleration, and elevation) during normal operation of literally thousands of vehicles for an extended period of time, the research team will develop a statistically meaningful dataset describing how trucks are used across a broad range of trucking applications. This data will then be used to analyze the benefits that advanced FE and emissions technologies can provide for specific trucking applications.

8.1.2 Leveraging the Gains for the HTDC/MTDC Efforts

Multiple federal agencies are involved with various facets of truck operation in the United States (e.g., FE by DOE, safety by DOT/FMCSA, emissions by EPA). Often, agencies such as these conduct testing independently, involving significant replicative costs. Future research would benefit considerably by collaborating and conducting testing in a coordinated manner. In this way, the cost of the data collection efforts would be decreased; more data could be collected; and the relationships that exist between FE, safety, and emissions could be more thoroughly investigated, providing results that holistically consider all facets of truck operation. The MTDC efforts conducted in this project demonstrated that FE and safety testing (albeit limited in scope) could be conducted together. A workshop should be held that brings together stakeholders from various federal agencies who have an interest in heavy vehicle research and data collection to make them aware of the rich data set that exists as a result of the HTDC and MTDC efforts, as well as the tools that have been developed by ORNL. Further, collaborative discussions could be fostered to leverage this research to the benefit of future efforts.

8.1.3 Special Studies

The main focus of the HTDC and MTDC projects was on the FE of Class-6 to -8 commercial vehicles. However, the data collection included not only all the information required for a thorough analysis of FEs and the development of associated models, but also additional information that can benefit DOE, other federal and state agencies, and various industries and research institutions. The data collected in the HTDC and MTDC efforts, together with the DCGenT and other tools developed in conjunction with those efforts, could be used for a variety of additional analyses and special studies. For DOE those include the development of driver models that take advantage of the real-world data collected (as opposed to existing models that mostly rely on test-track data) and cost/benefit analyses of route optimization and its impacts on FE. For vehicle and engine modeling, research is needed to assess the variability within vocational duty cycles. High variability suggests significant opportunities to improve operations or to learn from more optimal duty cycles.

The data collected in these projects contains information that can be used to quantify the operation of vehicles in the real world, such as the number of lane change maneuvers per mile traveled (an important statistic related to truck rollover and therefore the safety of Class-8 trucks in particular), the number of hard-brake maneuvers per mile traveled, and even real-world stopping distances after a hard brake maneuver, all of them of interest to DOT agencies.

Some minor studies involving the extraction of particular types of information at the request of the automotive industry have already been performed. However, more detailed research in partnership with the industry should be carried out, particularly to help with modeling of the new class of hybrid engines currently being developed.

Research institutions and universities would certainly benefit and advance the state of the art in many areas if they could access and use the information collected in these projects. As part of the MTDC project, ORNL has developed a web-based tool to visually search and extract information from the large HTDC and MTDC databases. This tool should be further developed and tested to make the HTDC/MTDC readily available.

8.1.4 Collection of Additional Duty Cycle Data

Although the HTDC/MTDC data collection effort covered a limited number of vocations, it became evident from the analysis that there are significant differences in terms of operations and duty cycles among these vocations. The information collected in these projects permits the characterization of the five vocations in great detail for modeling, simulation, engine testing, and other research purposes. However, there are many other vocations and vehicle classes that are significant consumers of fuel about which little is known. Further duty cycle data collection efforts similar to MTDC could be performed for these other vocations and classes of vehicles. With the appropriate equipment and access to test vehicles, testing could be performed for more test vehicles, spread more widely across the country, to gain insight in the variability within each vocation, class, and environment.

8.2 TECHNOLOGY

8.2.1 Development of Streamlined Vehicle Data Bus Interrogation Methodology

For these efforts, , the DAS setup, a critical task in the data collection system, required intensive manual labor, particularly to identify the location of specific information in the vehicle data bus. This imposed a constraint in the selection of the fleets participating in the project, since they needed to be within driving distance from ORNL to minimize deployment costs. If the DAS setup task could be automated, then a data collection system that could be deployed remotely (i.e., equipment that shop personnel could easily install with no need for researchers to be physically in contact with the instrumented vehicles) could be achieved. This would increase efficiency and allow deployment of the data collection equipment on fleets anywhere in the nation and even abroad (e.g., for Department of Defense data collection purposes). Future research should be devoted to investigating and developing methodologies, hardware, and software to streamline the DAS setup and achieve a fully automated, remotely controlled data collection and data access system.

8.2.2 Refinement of DCGenT

Research to commercialize a synthetic DCGenT with the goal of widespread acceptance would provide a quantitative base upon which to direct research and provide some standardization to vocational duty cycles. Federal and private entities, such as EPA or engine manufacturers, could benefit from a set of synthetic duty cycles developed for a set of vocations using the DCGenT. In a similar vein, an HTDC/MTDC analysis center could be established to respond to federal and private requests. If requests are made that are of interest to both DOE and the industry, the study could be jointly funded; studies of interest to industry only could be done on a cost recovery basis.