Final Scientific/Technical Report

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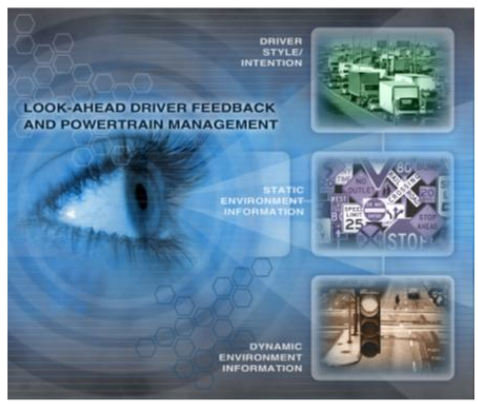
Recipient Organization: Eaton Corporation
W126N7250 Flint Drive
Menomonee Falls, WI 53051



Principal Investigator: Rajeev Verma, PhD
Eaton Corporation
26201 Northwestern Highway
Southfield, MI 48076
(248) 226-6413
RajeevVerma@eaton.com

Contractual Contact: Cindy K. Shane, Manager, Government Contracts
(414) 449-6607, Lucindakshane@eaton.com

Partners: University of Michigan Transportation Research Institute
Oak Ridge National Laboratory

DUNS Number: 360921261

DOE Project Officer: David Ollett, (412) 386-7339, David.Ollett@NETL.DOE.GOV

DOE HQ Contact: Leo Breton, (202) 586-9003, Leo.Breton@ee.doe.gov

DOE Contract Specialist: Bethan Young, (412)386-4402, Bethan.Young@NETL.DOE.GOV

Acknowledgement, Disclaimer, and Proprietary Notice

Acknowledgment

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Proprietary Notice

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Table 1: List of Abbreviations

Abbreviation	Description
ADASRP	Advanced Driver Assistance System Research Platform
BOM	Bill of Material
CAN	Controlled Network Area
CoC	Certificate of Confidentiality
CDL	Commercial Driving License
DoE	Department of Energy
DoT	Department of Transportation
DSRC	Dedicated Short Range Communication
DVI	Digital Visual Interface
EECU/TECU	Engine or Transmission Electronic Control Unit
FE	Fuel Economy
GA	Grade Adaptation
GID	Geometric Intersection Description
GPS	Global Positioning System
HMI	Human Machine Interface
HTDC	Heavy Truck Duty Cycle
HW/SW	Hardware/Software
IRB	Institutional Review Board
ITS	Intelligent Transportation System
IVBSS	Integrated Vehicle Bases Safety System
LAFE	Look-Ahead Fusion Engine

LH	Line-Haul
LPM	Look-Ahead Driver Feedback & Powertrain Management Technology
MSDTE	Mass Specific Driving Tractive Energy
OEM	Original Equipment Manufacturer
P&D	Pickup & Delivery
RSE	Road Side Equipment
SBC	Single Board Computer
SPaT	Signal, Phase and Time
VNT	Vehicle Networking Toolbox
V2X	Vehicle to X (X can be Vehicle (V2V) or Infrastructure (V2I))

1.0 EXECUTIVE SUMMARY

Commercial medium and heavy vehicles, though only a small portion of total vehicle population, play a significant role in energy consumption. In 2012, these vehicles accounted for about 5775.5 trillion btu of energy consumption and 408.8 million tons of CO_2 emissions annually, which is a quarter of the total energy burden of highway transportation in the United States [1]. This number is expected to surpass passenger car fuel use within the next few decades. In the meantime, most commercial vehicle fleets are running at a very low profit margin. It is a well-known fact that fuel economy can vary significantly between drivers, even when they operate the same vehicle on the same route. According to the US Environmental Protection Agency (EPA) and Natural Resource Canada (NRCan), there is up to 35% fuel economy difference between drivers within the same commercial fleet [2] [3], [4]. Similar results were obtained from a Field Operation Test conducted by Eaton Corporation [5]. During this test as much as 30% fuel economy difference was observed among pick-up-and-delivery drivers and 11% difference was observed among line-haul drivers. The driver variability can be attributed to the fact that different drivers react differently to driving conditions such as road grade, traffic, speed limits, etc. For instance, analysis of over 600k miles of naturalistic heavy duty truck driving data [5] indicates that an experienced driver anticipates a downhill and eases up on the throttle to save fuel while an inexperienced driver lacks this judgment.

In recent years, rapid progress in Intelligent Transportation Systems (ITS) has significantly increased availability of predictive road and traffic information at both vehicle level and fleet level. This information can be utilized to bring down the effect of driver variability on vehicle fuel consumption. The widespread acceptance of these technologies is making it feasible and affordable to reduce driver bias through enhanced driver feedback and/or powertrain automation. This will eventually lead to reduction in fuel consumption and potential monetary savings for a truck fleet. A reduction of 1% in fuel consumption translates to an annual saving of approximately $650 per vehicle, assuming the vehicle covers a distance of 100k miles in a year with a mileage of 6 miles per gallon and fuel cost of $4 per gallon.

Driver assistance systems can be categorized into two groups based on their means of influence. Passive assistance systems [8] are those where only advisory feedback is provided to the driver. In active assistance systems, system automation takes over some portion of vehicle control. Generally speaking, external non-vehicle related factors that impact fuel economy can be broken down into three categories: static environmental constraints, dynamic environmental constraints and operator's driving style. Static environment constraints include road geometry and posted speed limit which can be obtained with a combination of GPS and digital maps. Dynamic constraints, on the other hand, are about real-time traffic including relative speed, location of surrounding vehicles, traffic light phases, wind speed and direction, etc. Such information can be obtained through conventional on-board sensors such as Radar and Vision, or next generation information technology such as vehicle to vehicle (V2V) or vehicle to infrastructure (V2I) communication devices. Operator's driving style here means a driver's reaction to the static and/or dynamic environmental constraints.

The optimality of driver behavior and powertrain operation at current time depends on future conditions of the driver, vehicle and environment. Lack of knowledge of such future conditions often limits the effectiveness of these systems. Manzie, et al [6] demonstrated a potential 13-35% fuel economy improvement on selected urban driving cycles when future traffic information is stationary and visible for 50 seconds. Other research has been focused on utilizing predictive topographical information (which is relatively easy to obtain and more accurate) to reduce fuel consumption [7], [8], [9]. However, during a drive cycle, these technologies are usually operational when the driver engages cruise control and are aptly named predictive cruise control, etc. Technologies that act on such information while cruise control is engaged do not cover the whole operational zone of heavy duty vehicles. For instance, in our current study, a majority of pick-up and delivery drivers (5 out of 8) rarely used cruise control [6] . In addition, the benefit of cruise control focused technologies is maximized at highway speeds [4]. This leaves a large room for similar technologies that can operate in all speed ranges as well as in cruise control off driving situations as well.

The objective of this work is to develop and demonstrate an intelligent driver assistance technology that utilizes both static and dynamic environmental information to help the driver reduce unnecessary throttle request during the whole drive cycle (both cruise control on and off) through a combination of advisory driver feedback and driver-and-environment adaptive powertrain control. The main goals of this program are to develop and demonstrate the intelligent driver assistance system for reducing fleet average fuel economy for the whole drive cycle; conduct a pilot test allowing the drivers to experience the technology during their normal, day-to-day work; evaluate the fuel saving potential of this technology (in cruise control off mode only) and study commercial vehicle driver's acceptance of such systems.

The analysis of the data collected during the pilot test indicates that the proposed system was successful in the reduction of total fuel consumption during the treatment period when compared to the baseline period. The portion of drive cycle when the system is active comprises of section when no cruise control is engaged, vehicle speed is above 25 mph and no brake or turn-signal is active. When comparing the performance of the treatment period with the system active to the baseline period in similar driving conditions (no cruise control engaged, speed above 25 mph and no brake or turn-signal active time), a reduction of 6 percent in total fuel consumed was noticed. When compared to the fuel consumed over the complete baseline duty cycle, this number reduces to 2 percent. It is important to notice that in this study, the system is activated only when cruise control is not engaged; however, the system can operate in both cruise control modes. The total distance covered by all drivers with the system active was 6131 miles while a total distance of 7133 miles was covered with cruise control on. The fuel saving potential of the system might be higher if it covers the cruise control on situation as well.

As previously mentioned, the system utilizes the road topology data for the calculation of fuel optimal speed trajectory. The cumulative fuel saving over a drive cycle is dependent on the amount of drive cycle exposure to road topology variation (for example, uphill and downhill road features). Higher exposure will result in higher saving potential. Other factors that can influence fuel consumption are vehicle mass, vehicle speed and weather. In the overall fuel consumption analysis, the vehicle mass information was not utilized since this information was available for a relatively small number of trips. Additional analysis was performed that utilized drive cycle data along with vehicle mass to derive statistical representation of vehicle drive cycle resulting from the baseline and treatment data. This statistical description was then utilized to evaluate the benefit of the system. This analysis indicates a FE improvement of 1.74 percent for Pick-up and Delivery (P&D) drive cycles.

The average vehicle speed of a drive cycle can affect the vehicle fuel consumption [11] [12]. For a class 8 heavy duty vehicle, studies show that the lowest fuel consumption is attained at an average cycle vehicle speed within a range of 49 mph to 55 mph with the fuel efficiency getting worse as we move away from this range in both directions. During the pilot test, the average speed of line-haul operation in baseline was 59.1 mph while for treatment was 58 mph. This increase in average speed of 1.1 mph may negatively affect the fuel efficiency of baseline by about 0.6 percent. For P&D operation, the average speed for treatment was 43.1 mph while for the baseline was 43.6 mph which may positively affect the fuel efficiency of baseline by about 0.5 percent. Weather can also affect the fuel consumption [13], [14]. It is well known that ambient temperature affects the fuel economy of a vehicle. This study did not employ weather monitoring. However, the average temperature at the start location of the daily trips can provide a high level picture. Table 2 presents the average maximum and minimum temperatures at the start and end point of the trip. It can be noted that most of the average temperature differences in baseline versus treatment are below 5 °F. The only exceptions are drivers 103 and 104 (minimum average temperature difference of 6 °F between treatment and baseline), and drivers 7 and 8 (maximum average temperature difference of -6.1°F and minimum average temperature difference of -9.1°F between treatment and baseline). It is not clearly understood how this temperature difference affected the fuel consumption, but the resulting change may not be significant.

Table 2: Maximum and Minimum average temperature during baseline and treatment periods at Romulus, MI

Driver/Period	Max Average Temp in °F	Min Average Temp in °F
Driver1,2,101,102/Baseline	**80**	**61.4**
Driver1,2,101,102/Treatment	**80.8**	**58.1**
Driver 3,4,103,104/Baseline	**79.1**	**59.6**
Driver 3,4,103,104/Treatment	**81.6**	**65.6**
Driver 5,6,105/Baseline	**68**	**50.6**
Driver 5,6,105/Treatment	**69.5**	**51.7**
Driver7,8/Baseline	**60**	**45.6**
Driver7,8/Treatment	**53.9**	**36.5**

Another important contribution of this research is the study of driver acceptance of the proposed system. It is easier to modulate the vehicle behavior when active assistance is being executed (for example predictive cruise control or automatic cruise control). However, the proposed system has components of both active as well as passive assistance. Due to this nature of the system behavior, a Human Machine Interface is an integral part of this system that provides the necessary interaction and feedback to the driver. During the field trial, drivers were interviewed about their experience with the system. Overall, drivers appeared to agree that it was easy to understand how the system operated, was engaged, and how it was overridden. Drivers generally agreed that the system saved fuel on both freeways and city streets, although there appeared to be less certainty about city streets. This may be due to the fact that, on a small percentage of roads, there was a difference in the speed limit provided by map database and the street speed limit. This also resulted in some concerns about the accuracy with which the display reflected road conditions. With respect to control authority and operations, drivers seemed confident that they were able to distinguish when they or the LPM had control authority. Finally, most drivers believed that the display was easy to understand.

2.0 COMPARISON OF ACCOMPLISHMENTS TO GOALS AND OBJECTIVES

The objectives of the project are:

- Develop the look-ahead driver feedback and powertrain management (LPM) technology that will assist commercial vehicle drivers to operate the vehicle more efficiently based on GPS, digital map and real-time traffic information obtained either from on-board sensors or vehicle to vehicle and vehicle to infrastructure communication.
- Demonstrate the technology on two instrumented commercial vehicles with professional drivers.

The project accomplished both objectives through the development and demonstration of LPM technology leading to a successful pilot test on two trucks that are a part of Con-way fleet. These trucks carried out their normal day-to-day fleet operation over a period of four months with a total of thirteen drivers who participated in the study for a period of four weeks each.

The major accomplishments of the project throughout the three phases along with the reports generated are listed below:

Phase I: Technology Development (10/2011 – 1/2013)

- Functional specifications of the proposed system defined
- Developed and implemented the look-ahead fusion engine on a prototype truck
- Established feedback strategies to the driver
- Developed candidate human-machine interface and driving scenarios for driving workload simulator study

Reports submitted to DoE:

- System Functional Specification Document (Eaton)

Phase II: Prototype Development (1/2013 – 1/2014)

- Executed driving simulator workload study and analysis of data to inform HMI down-selection
- Integrated the prototype system on a prototype vehicle and verified system functionality
- Developed a data acquisition system (DAS) and verified its functionality on the prototype truck
- Obtained commitment from a Con-way for pilot test

- Investigation of fuel saving potential from V2X technology and recommended features for widespread use of this technology to enable el saving benefit

Reports submitted to DoE:

- Human-Machine interface functional description and technical specification (UMTRI)
- Simulator Evaluation of Fuel Efficiency Advisor Driver-Vehicle-Interface Components (UMTRI)
- Look-Ahead Feedback and Powertrain Management System – Functionality Validation Plan (UMTRI)

Phase III: Technology Demonstration (1/2014 – 12/2014)

- Pilot vehicle integration design and preparation for pilot test
- Retrofitted 2 trucks owned by the participating fleet with:
    - A full sensor suite of forward radar, GPS, digital mapping, and communication systems
    - The prototype hardware and interface
    - The data acquisition system
- Conducted a pilot test and collect field data with drivers from the participating fleet
- Collected subjective driver/fleet feedback on the prototype system, identify the trade-off between driver acceptance and fuel cost saving, as well as remaining barriers for commercialization
- Evaluated fuel consumption and driver behavior impact of the technology

Reports submitted to DoE:

- Experimental test plan for phase III field study (UMTRI)
- Look-Ahead Feedback and Powertrain Management System – Functionality Validation Report (UMTRI)
- Look-Ahead Feedback and Powertrain Management System – Final Report (UMTRI)
- Evaluation of Fuel Efficiency Benefits for the Eaton Look-Ahead Powertrain Management System (ORNL)

3.0 SUMMARY OF PROJECT ACTIVITIES

The following sections present the project goals for the three phases and corresponding accomplishments.

Task 1.0 - Project Management

Task 1 comprises of activities that include project management and reporting. All quarterly and annual reports were submitted on time. In addition, an annual on-site and off-site project status update was presented to DoE. The on-site review was carried out primarily at Eaton's Southfield office and the annual review was presented at the DoE's annual meeting in Washington D.C. Table 3 below shows a list of Task 1 Activities with start and finish dates.

Table 3: Task 1 Activities

Task Name	Start	Finish
Task 1: Program management & Planning	**Mon 11/7/11**	**Thu 10/30/14**
Phase I	**Mon 11/7/11**	**Wed 1/30/13**
Project team kick-off meeting	Mon 11/7/11	Mon 11/7/11
1.1 Initial briefing	Wed 11/30/11	Wed 11/30/11
1.2 Research Performance Progress Report Q1	Mon 1/30/12	Mon 1/30/12
1.3 Research Performance Progress Report Q2	Mon 4/30/12	Mon 4/30/12
1.4 Annual program merit review (Year 1)	Fri 5/18/12	Fri 5/18/12
1.5 Research Performance Progress Report Q3	Mon 7/30/12	Mon 7/30/12
1.6 Research Performance Progress Report Q4	Mon 7/30/12	Mon 7/30/12
1.7 Annual report (Year 1)	Tue 10/30/12	Tue 10/30/12
1.8 Research Performance Progress Report Q5	Wed 1/30/13	Wed 1/30/13
Phase II	**Tue 4/30/13**	**Thu 1/30/14**
Research Performance Progress Report Q6	Tue 4/30/13	Tue 4/30/13

Annual program merit review (Year 2)	Thu 5/30/13	Thu 5/30/13
Research Performance Progress Report Q7	Tue 7/30/13	Tue 7/30/13
Research Performance Progress Report Q8	Tue 7/30/13	Tue 7/30/13
Annual report (Year 2)	Wed 10/30/13	Wed 10/30/13
Research Performance Progress Report Q9	Thu 1/30/14	Thu 1/30/14
Phase III	**Wed 4/30/14**	**Thu 10/30/14**
Research Performance Progress Report Q10	Wed 4/30/14	Wed 4/30/14
Annual program merit review (Year 3)	Fri 5/30/14	Fri 5/30/14
Research Performance Progress Report Q11	Wed 7/30/14	Wed 7/30/14
Final report	Thu 10/30/14	Thu 10/30/14

Task 2.0 - Baseline Specifications Development

Table 4: Task 2 Activities

Task Name	Start	Finish
Task 2: Baseline Specifications Development	**Mon 10/3/11**	**Fri 9/28/12**
2.1 Voice of the customer validation and functional requirements	**Mon 10/3/11**	**Fri 9/28/12**
Fleet interview	Mon 10/3/11	Fri 6/29/12
Functional requirements inputs collection	Tue 1/3/12	Fri 9/28/12
2.2 High FE impact behavior and scenario identification	**Wed 1/18/12**	**Fri 8/24/12**
Scenario segmentation based on existing data	**Wed 1/18/12**	**Fri 6/29/12**
Characterization of curves and grades & associated FE	Wed 1/18/12	Tue 4/3/12
Characterization of in-traffic driving & associated FE	Fri 2/24/12	Wed 6/27/12
Characterization of turns and stops & associated FE	Thu 2/9/12	Wed 6/13/12
Select targeted scenarios to study using existing data	Mon 4/16/12	Fri 6/29/12
Scenario-specific FE impact analysis	**Mon 4/16/12**	**Fri 7/6/12**
Potential FE impact for one scenario set	Mon 4/16/12	Tue 5/15/12
Potential FE impact for second scenario set	Wed 5/23/12	Fri 7/6/12
Deep dive on two selected scenarios	Mon 7/9/12	Wed 8/15/12
Finalize the driving scenarios and driver behaviors to be addressed by the system	Fri 8/24/12	Fri 8/24/12

Subtask 2.1: Voice of the Customer Validation and Functional Requirements

Interviews were carried out with two large fleets. The purpose of the interview was to listen to the main concerns that the fleet managers are facing as well as to gauge their interest in the proposed technology. Various implementation options were evaluated and suppliers were identified. The main findings were reported in a progress report submitted to DoE in 2012.

Subtask 2.2: High FE Impact Behavior and Scenario Identification

Task 2.2 consists of an analysis of existing field operational test data from the IVBSS project [5], in which over 600,000 miles of continuous data were collected. This work was conducted by UMTRI and Eaton. The analysis steps include a general look at the Fuel Efficiency (FE) behavior of drivers in a set of scenarios, including curves, turns and stops ("down-speed" scenarios), and grades ("speed-keeping" scenarios"). This study was to determine:

- How to extract the scenario of interest from the field test data
- The fraction of total driving distance that the scenario represents, as a function of route type (line-haul or pick-up and delivery)
- A preliminary estimate of the fraction of fuel that could be conserved, were all the drivers to perform as well as the best driver.

The second part of Task 2.2 includes looking in more detail at two of the scenarios in order to quantify the potential FE impact of that scenario. This task was completed and the findings were reported in a progress report submitted to DoE in 2012.

Task 3.0 - Prototype Design

Table 5: Task 3 Activities

Task Name	Start	Finish
Task 3: System Design	**Mon 10/3/11**	**Tue 1/15/13**
Functional specification (milestone 3.1)	Mon 10/3/11	Fri 9/28/12
3.1 Look ahead fusion engine (LAFE) development	**Mon 10/3/11**	**Tue 1/15/13**
Gen 1 LAFE Development (milestone 3.2)	**Mon 10/3/11**	**Tue 1/15/13**
DSRC integration	**Tue 10/18/11**	**Fri 6/29/12**
DSRC device functionality validation (milestone 3.2.1)	Tue 10/18/11	Wed 2/15/12
DSRC integration with Michigan Test-bed	Thu 2/16/12	Fri 6/29/12
DSRC integration on the prototype vehicles (milestone 3.2.2)	Thu 2/16/12	Fri 3/30/12
Gen 1 LAFE hardware development	**Mon 10/3/11**	**Tue 1/15/13**
Identify gaps between current HERE ADASRP and stand-alone map unit	Mon 10/3/11	Fri 1/27/12
LAFE HW design down selection (milestone 3.2.3)	Mon 10/3/11	Fri 3/30/12
LAFE HW design finalization	Mon 4/2/12	Fri 6/22/12
Stand-alone Map Unit Development	Mon 4/2/12	Fri 9/28/12
Gen 1 LAFE HW integration on prototype truck	Mon 6/25/12	Tue 1/15/13
Gen 1 LAFE HW on the prototype truck (milestone 3.2.4)	Tue 1/15/13	Tue 1/15/13
Gen 1 LAFE software development	**Mon 10/3/11**	**Tue 1/15/13**
Initial LAFE SW (with Radar and HERE ADASRP)	Mon 10/3/11	Fri 12/30/11
Refinement of throttle management with prototype vehicle	Tue 1/3/12	Fri 6/29/12
Decide on the interface to HMI (content and communication protocol)	Mon 4/2/12	Mon 4/2/12
Integration of DSRC information into traffic estimation SW	Mon 4/2/12	Fri 6/29/12
Update target speed based on DSRC input	Mon 7/2/12	Fri 11/2/12

Gen 1 LAFE SW release (milestone 3.2.5)	Tue 1/15/13	Tue 1/15/13
3.2 Human-machine Interface Concept Development (milestone 3.3)	**Tue 4/3/12**	**Mon 12/24/12**
Scope out interface concepts-identify possible displays based on scenario-specific analysis	Tue 4/3/12	Mon 7/23/12
Develop simulator-based display hardware	Tue 7/24/12	Mon 10/15/12
Design simulator study	Tue 7/24/12	Mon 12/24/12

Subtask 3.1 Look-Ahead Fusion Engine (LAFE) Development

Subtask 3.1 lists the progress in development of LAFE hardware, LAFE software and other critical components

Subtask 3.1.1 DSRC Device Functionality Validation, Integration on the Prototype Truck and Integration with Michigan Test Bed

Vehicle to vehicle (V2V) communication: This task involved testing the functionality of Dedicated Short Range Communication (DSRC) box on the host vehicle (vehicle equipped with LAFE) to receive messages from a DSRC box residing on another vehicle to enable V2V communication. This task was completed and demonstrated through an on-road test.

Vehicle to infrastructure (V2I) communication: This task involved testing the functionality of the DSRC box to receive messages from roadside equipment (RSE) units installed in Michigan Connected Vehicle Test Bed. These messages need to be decoded on the Look-ahead fusion engine and produce signal phase and time (SPaT) remaining for the change of the phase for each approach and lane at the intersection. This task has been completed and demonstrated through an on-road test. Figure 1 displays the lane layout information received in the GID message from the RSE units and the traveled path of the truck. Look-ahead fusion engine utilizes this information to identify the correct lane and extract the right SPaT information from the SPaT message sent out by the RSE unit.

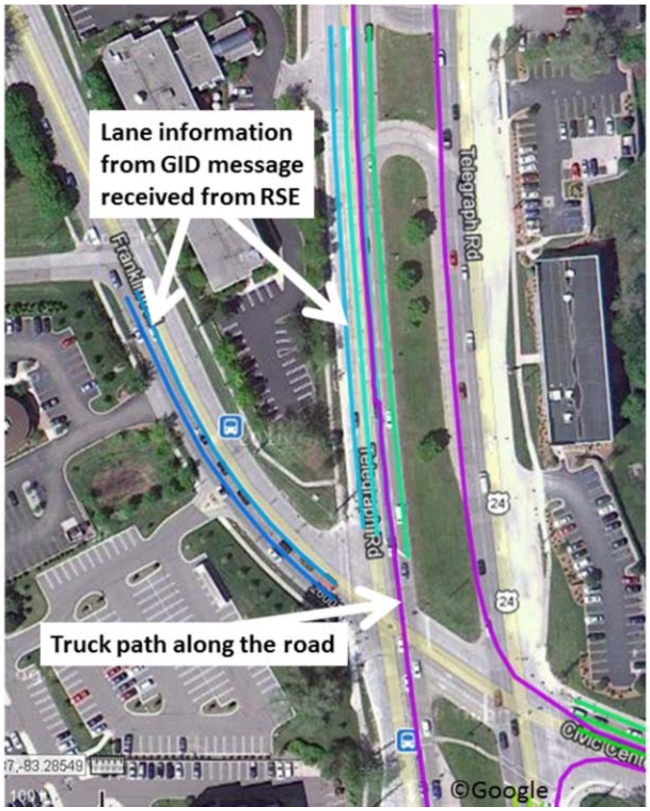


Figure 1: V2I integration with Look-ahead fusion engine

Figure 2 shows results from V2V exposure on Telegraph road test-bed. The x-axis of the plot shows time in seconds. The bottom sub-figure shows the time in seconds for the intersection light to change while the middle sub-figure shows the phase of intersection light. A value of 4 on middle sub-figure corresponds to a red light and a value of 2 corresponds to green light. The top sub-figure shows a flag that suggests whether the driver should stop (value of 0) or keep going (value of 100). Figure 3 and Figure 4 show the comparison of V2V sensor with radar. Figure 3 shows the distance between the host and lead vehicle with V2V and radar. The notable difference between the two is that a) the data from V2V sensor is coming in at a rate of 1 sample per second and 2) there is a small delay between the V2V and radar reading. The two readings match closely except for the initial part of the plot where the lead vehicle is not in front of the host vehicle (for example, while turning). In this case, radar loses sight of the lead vehicle whereas V2V sensor can still receive messages. The observations above are true for range rate signal as well (Figure 4). The V2V sensor was utilized to modulate the speed of host vehicle when the lead vehicle was too close to the host vehicle. This technology, when augmented with appropriate lane identification technology (for example, based on 3D map input and V2V data) can result in a relatively low cost replacement to radar in the future.

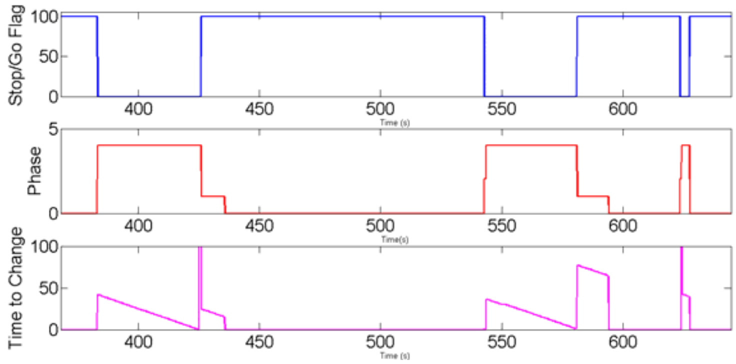


Figure 2: Results from V2I experiment

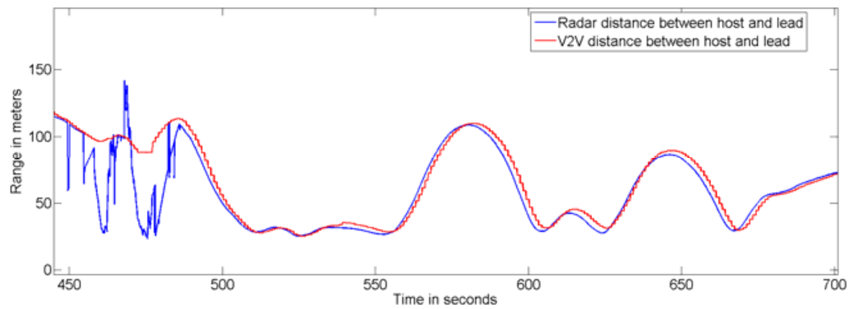


Figure 3: Comparison of relative distance between host and lead vehicle with V2V and radar

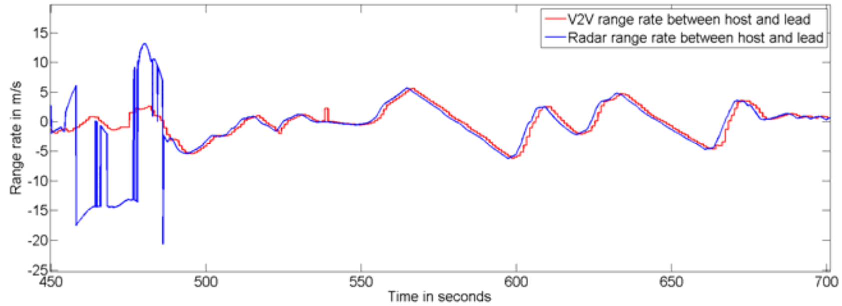


Figure 4: Comparison of range rate between host and lead vehicle with V2V and radar

The functionality of both V2V and V2I was demonstrated with both generation of LAFE hardware as described in the next section. In Phase I, this hardware platform comprised of a PC-104 embedded target platform and in Phase II the hardware platform was replaced by a single board computer (SBC), as described in the next subtask.

Subtask 3.1.2 LAFE hardware development

The implementation of this system required a robust hardware platform that could host the required software components, interface with multiple devices over different communication protocols and be able to operate in real time while operating in a harsh commercial vehicle environment. The hardware should be able to have functionalities such as start on truck key-on, turn off at truck key-off, program auto-start and auto-stop. The first version of the modularized system is shown in Figure 5. This system includes GPS based map database, mobile broadband traffic information, and on-board vehicular radar with interface to V2x channels. The proprietary LPM algorithm resides in an embedded computer PC104. The GPS sensor, V2x, and radar/camera sensor are hooked to the PC 104 directly, while a laptop with map database and broadband wireless access is connected to PC 104 through CAN communication. The wireless connection provides real-time traffic information. This earlier prototype system can work effectively with the Eaton UltraShift Plus powertrain system on a Class 8 long-haul truck.

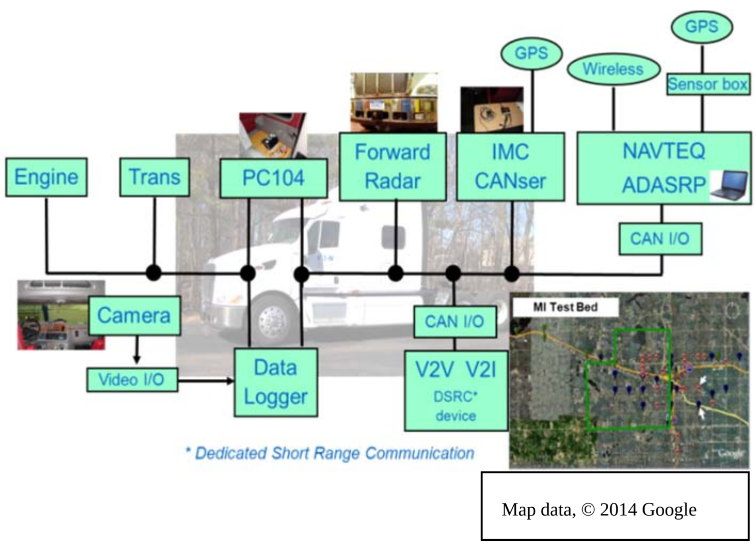


Figure 5: Distributed LPM System

SBC Based Modularized LPM Architecture

The above distributed system cannot be deployed handily for fleet trials. In order to have quick delivery of a centralized modular system for field testing, new system architecture was developed. The selected hardware needs to conform to automotive grade usage, subject to the real-world applications. This requires the on-board system to work reliably under the exposure of drastically varying temperatures, significant vibration and impact, and certain adverse EMI. Furthermore, standard communication protocols are recommended for data exchange between various data resources in order to improve the reliability and minimize the development effort.

The NAVTEQ (now known as HERE) map database, advanced driver assistance system research platform (ADASRP), is used for providing the geographic information and speed limits along the driving road. Both road grade and speed limits are key variables on how to operate a vehicle more effectively efficiently. The database for North American version is about 20GB. The NAVTEQ software supports both virtual and physical CAN communications, and needs to receive GPS location information from the NAVTEQ sensor box. This sensor box, which also contains an analog vehicle sensor, has a serial communication port that outputs the sensing data.

ADASRP has a feature to access the broadband wireless traffic information so that the real-time and historic traffic data can be provided for powertrain/vehicle management. For this application, the Sprint 3G Mobile Broadband Network is chosen to connect the vehicle to the traffic information server. The minimum system requirements for installation and operation of Sprint SmartView is Window OS with 70MB of hardware drive and faster than 300MHz of microprocessors.

The Dedicated Short Range Communication (DSRC) device is connected to the LPM system via an Ethernet connection. Both Signal Phase and Timing (SPaT) information, from signaled intersections using V2I communication and V2V information, is received through DSRC. The AC20 forward-looking radar module has a dedicated CAN bus for providing the relatively large amount of data from the radar sensors. This 5.8GHz short-range side-radar unit is mounted on the front side of the heavy-truck chassis. The radar unit can detect the presence of objects adjacent to the current vehicle at a maximum detection range of at least 4 meters and an azimuth field-of-view of 100 degrees.

In order to meet the communication setup and data processing capability as discussed above, a single board computer (SBC) with Window Operating System is selected as a central unit to host the LPM control algorithm. The first selection was ARK-3202 [12], which has a 1.6GHz processor and supports 2GbE, 5 USB 2.0 and max to 5 COMs ports. The hardware drive can be expanded to meet the needs to accommodate the map database, ADASRP software, Sprint driver, and the LPM control software developed in Matlab/Simulink by Eaton. Furthermore, it is worth noting that this SBC is designed for automotive application, ensuring maximum reliability with wide temperature ranges of -40~80^{0}C and anti-Vibration mechanism. Figure 6 presents the SBC based LPM system. Ethernet is used to interface to DSRC, i.e., V2V and V2I. NAVTEQ sensor box is connected to the SBC through a serial-to-USB converter; while the USB based Mobile broadband device is connected to SBC directly. CAN communication is based on Vector CAN devices.

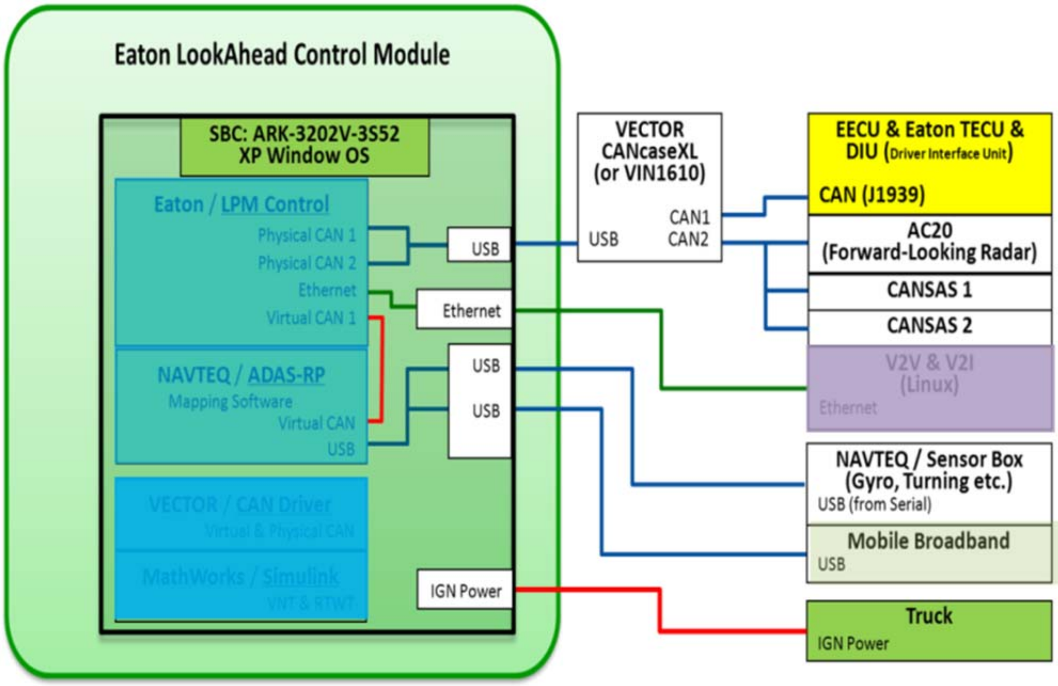


Figure 6: SBC based Modularized LPM System

Subtask 3.1.2 LAFE software development and controller validation

The development of LAFE software was completed in Phase II. The system utilizes future road topological and traffic information to differentiate between driver-caused and environment-caused inefficiency. It consists of four major modules: Environment Recognition, Driver Behavior Recognition, FE-optimal Behavior Estimation and Decision Making (Figure 7). The input of the system can come from a variety of sensor and information systems, which includes both conventional on-board sensors such as radar, vision, vehicle database and technologies such as GPS, 3D digital maps, as well as vehicle-to-vehicle and vehicle-to-infrastructure communication devices. The output of the system can be engine torque/speed control, transmission shift control and advisory driver interface (audio/visual). Braking is not considered as an active control as it does not contribute to fuel saving and introduces safety risks. The Environment Recognition module fuses information from various sensors and identifies the upcoming environment condition. The FE-optimal Behavior Estimation module derives the optimal driving profile that includes acceleration intensity and gear shift timing. In parallel to the Environment Recognition and FE-optimal Behavior Estimation module, the Driver Behavior Recognition module accumulates historical driving data under different environment conditions and builds a statistical model to estimate the driver’s current and future intent. In particular, this module is responsible for recognizing safety and performance critical events such as passing and merging so that the level of driver assistance can be reduced, delayed or completely suppressed during these events.

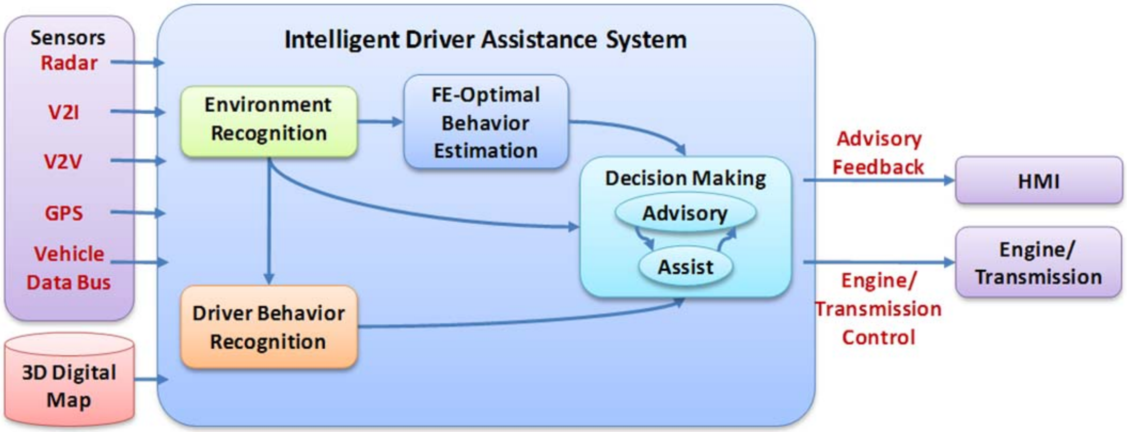


Figure 7: Look-Ahead Powertrain control system framework

This information is fed into the Decision Making module, which decides whether or not to influence the driver and vehicle behavior to achieve the best fuel economy. The factors considered here include (1) the difference between the driver demand/intent and the FE-optimal behavior, and (2) the nature of the perceived driver intent, i.e. whether safety and performance are critical or not. In the case that driver assistance is needed, the module will further decide whether to provide advisory feedback to the driver or actively assist the driver through powertrain automation, e.g. gear shifting and engine torque/speed control or a combination of both. The choice between advisory feedback and active assistance is going to be based on not only the associated safety and drivability risks and the accuracy of the Environment Recognition output, but also on how the driver behavior deviates from the FE-optimal behavior and the expected driver responsiveness. We would like to emphasize that a combination of advisory feedback and active assistance is necessary in order to address fuel consumption and emission reduction needs across the general commercial fleets, as each approach has its own limitation and advantage under specific conditions. For example, active control of engine speed/torque and transmission gear ratio is the preferable way of achieving vehicle speed modulation as a function of road topology during high-speed highway driving. However, when the driver is in constant acceleration and deceleration during traffic-following or city maneuvering when sensor information is often imperfect, advisory feedback can help mitigate safety and performance risks introduced by false intervention. In addition, the traffic information granularity was found to be low and had to be weighted appropriately for active assistance. A driver interface constantly keeps the driver updated of the current system state (system off, system on or driver in control). In the next section, we discuss some representative scenarios that can be implemented in the proposed system. A Simulink based speed trajectory following vehicle model that is equipped with a fuel consumption model was verified against on-road fuel consumption test data and utilized for this study.

Scenario 1: up-speed transition

In this example, we study the up-speed transition scenario, when the driver's mission is to transition from a full stop (i.e. 0 speed) to a target speed of 45mph through a fixed travel distance. Examples of such scenario include an on-ramp or the initial road segment after a stop sign. Various driver behaviors were examined through this experiment, in which a driver can choose different speed transition strategies. Intuitively, one would think gentle acceleration will lead to the best FE. However, as Figure 8 shows, in this case, it is more efficient to accelerate to 45mph at maximum rate and maintain the speed afterwards. Similar results have been observed in other initial and final speed conditions in this scenario, which tells us driving faster or aggressively does not always mean low FE, and saving fuel and reducing trip time are not necessarily two conflicting objectives. The trick here is that we are not comparing different accelerations behaviors, but rather different behavior choices that a driver has in order to meet the environment constraints, which is to change the speed from 0 to 45mph before the end of an on-ramp or before merging into the main traffic. As a result, the most appropriate driver assistance strategy under this scenario is to let (or encourage) the driver accelerate as fast as possible to establish the target speed and maintain it. Hard acceleration will still lead to low fuel economy but only during acceleration, but the efficiency loss will be offset by entering high-efficiency state earlier. This example has demonstrated how the separation of environment factors can help us discover the true relationship between driver behavior and fuel consumption, which can be very counterintuitive.

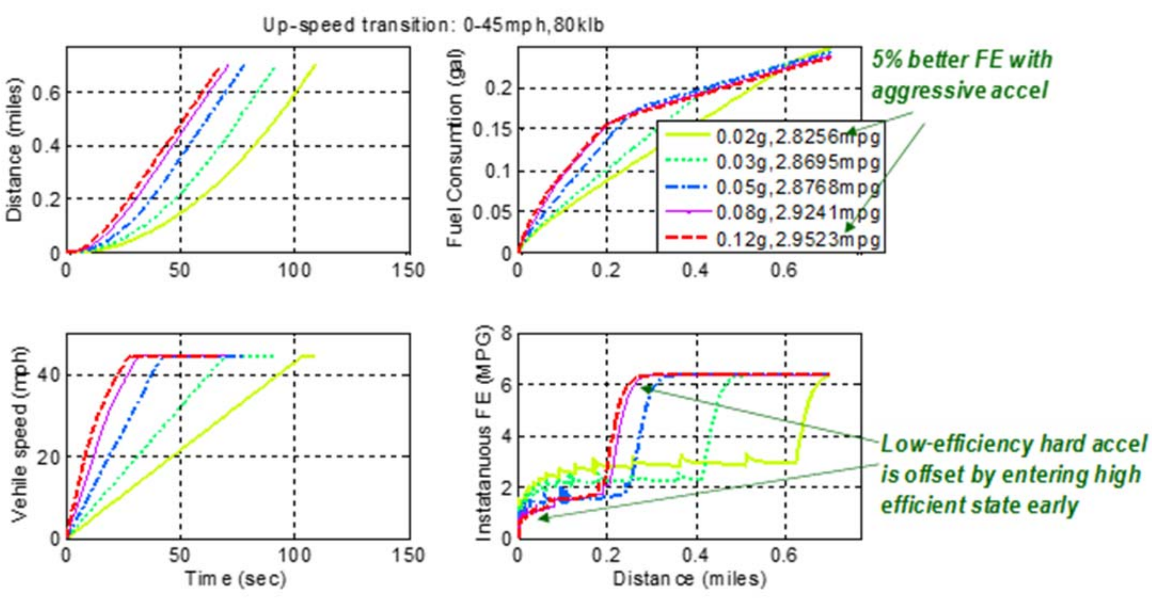


Figure 8: Behavior impact on fuel economy during up-speed transition

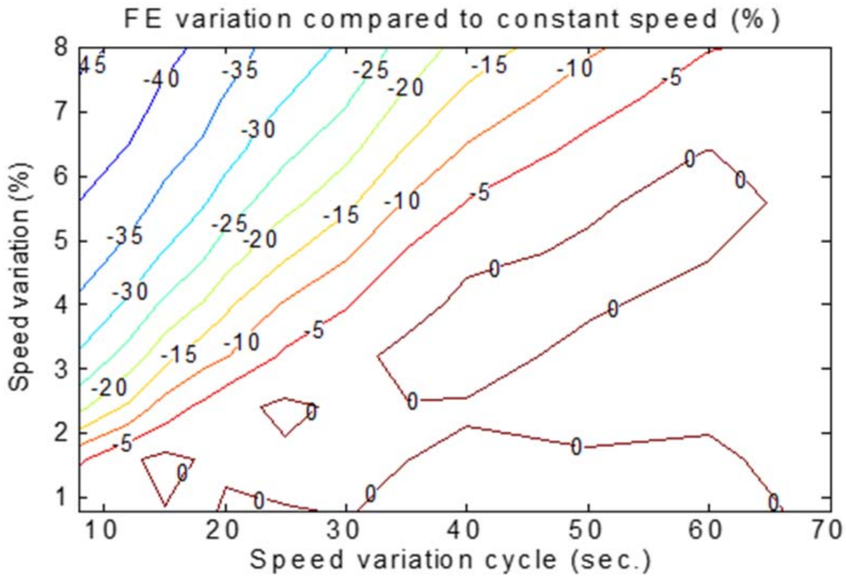


Figure 9: Speed-keeping behavior and its impact on fuel economy (FE)

Scenario 2: speed-keeping

In this example, the impact of speed-keeping behavior on fuel consumption is evaluated. The baseline scenario is the case when the vehicle is running at a constant speed. For comparison, various speed-keeping behaviors are simulated, which resulted in different levels of speed change and speed change frequency. Figure 9 above shows the result from one experiment where the baseline speed is 25m/s on a flat road, the magnitude of speed change varies from 1% to 8%, i.e. from 0.25m/s to 2m/s, and the frequency of speed change varies from 1/10 Hz to 1/70 Hz. As the result indicates, even a 5% speed variation with a modest change rate (i.e. 0.1Hz) can result in more than a 35% penalty of fuel economy compared to the baseline. The implication here is that even speed variation at a micro level will have significant impact on fuel consumption. Therefore, an engine torque control strategy to minimize unnecessary speed change at micro level is an appropriate and valuable or valued added approach. This strategy can be utilized in traffic following situation where there is a large variation in the overall traffic speed however, the system results in the vehicle speed following a smoother trajectory.

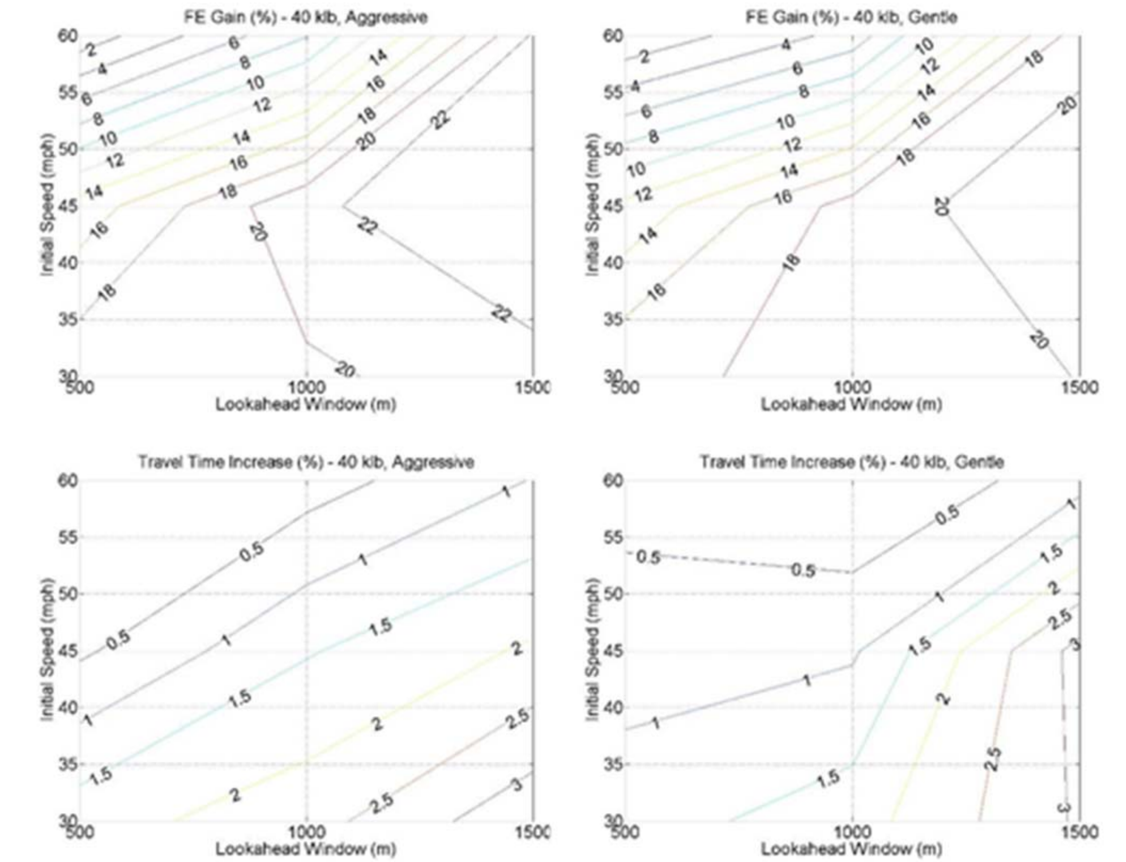


Figure 10: Behavior impact on fuel economy during down-speed transition

Scenario 3: Down-speed Transition

In this example, we investigate the fuel saving potential in a down-speed transition situation. Examples of such situations include an exit ramp and the road segment leading toward a stop sign. The set of this experiment is exactly the opposite of the up-speed transition case. Here the driver starts at a non-zero speed and needs to bring the vehicle to a stop at a fixed distance. Various initial speeds were simulated from within a 30mph to 60mph range. Two different types of driver behavior, gentle and aggressive, were also simulated to establish two different baseline driver behaviors. An aggressive driver will maintain his initial speed a lot longer before slowing down and eventually stop at the end distance. The FE-optimal behaviors with respect to different look-ahead windows (from 500m to 1500m) were estimated and the corresponding fuel economy and travel time for each case was compared to that of the two baselines. The results are shown in Figure 10 above. As the two plots for FE gain demonstrated, the difference between the baseline driver behavior and the FE-optimal behavior is very small when the initial speed is high (i.e. around 60mph) and the look-ahead window is short (i.e. around 500m), which should not be too surprising. When the initial speed is high, even an aggressive driver is likely to start slowing down at the time when the vehicle approaches a small look-ahead window. However, when the look-ahead window is sufficiently long with respect to the initial speed, we can see that FE difference between the optimal behavior and the two baselines here can be as much as 20%. It is worth noting that the time increase introduced by the FE-optimal behavior (by entering the coasting stage early) is very minimal (< 3s) in this case. Although the magnitude of fuel consumption during down-speed transition is very small compared to other scenarios, the main benefit of the FE-optimal behavior comes from reducing the unnecessary speed-keeping behavior at the beginning of the down-speed transition scenario.

Scenario 4: GRADE adaptation

This scenario demonstrates the utilization of predictive grade information for improvements in fuel efficiency. During conventional highway driving, a commercial vehicle spends most of its time running at maximum speed limits or the highest governed speed specified by the fleet operator. In conventional speed tracking devices, such as engine control based speed governors or cruise control, any change in the road grade is treated as a disturbance. The controller thus compensates for a step increase in road grade by a step increase in engine torque, which results in torque transients. Moreover on a downhill, braking may be applied to maintain speed, which results in wasted fuel. One strategy to avoid this is to use predictive grade information to anticipate upcoming change in the grade and to either gain or lose kinetic energy before an uphill or downhill, by speeding up or slowing down [7]. Simulation results show that by adopting such a strategy, for a heavy trailer having a total gross weight of around 70,000lbs, a fuel saving of 1.05% can be achieved for an uphill and 1.21% for a downhill (Figure 11 (a) and (b)) for a ±5% speed variation range of the road speed limit. The savings increase is 1.92% for uphill and 2.62% for downhill, when the speed variation band is increased to ±10% of the road speed limit (Figure 11 (c) and (d)) can be seen from the simulation results.

Table **6** shows a summary of the simulation results for both truck without a trailer (20,000lbs) and truck with a heavy trailer (70,000lbs).

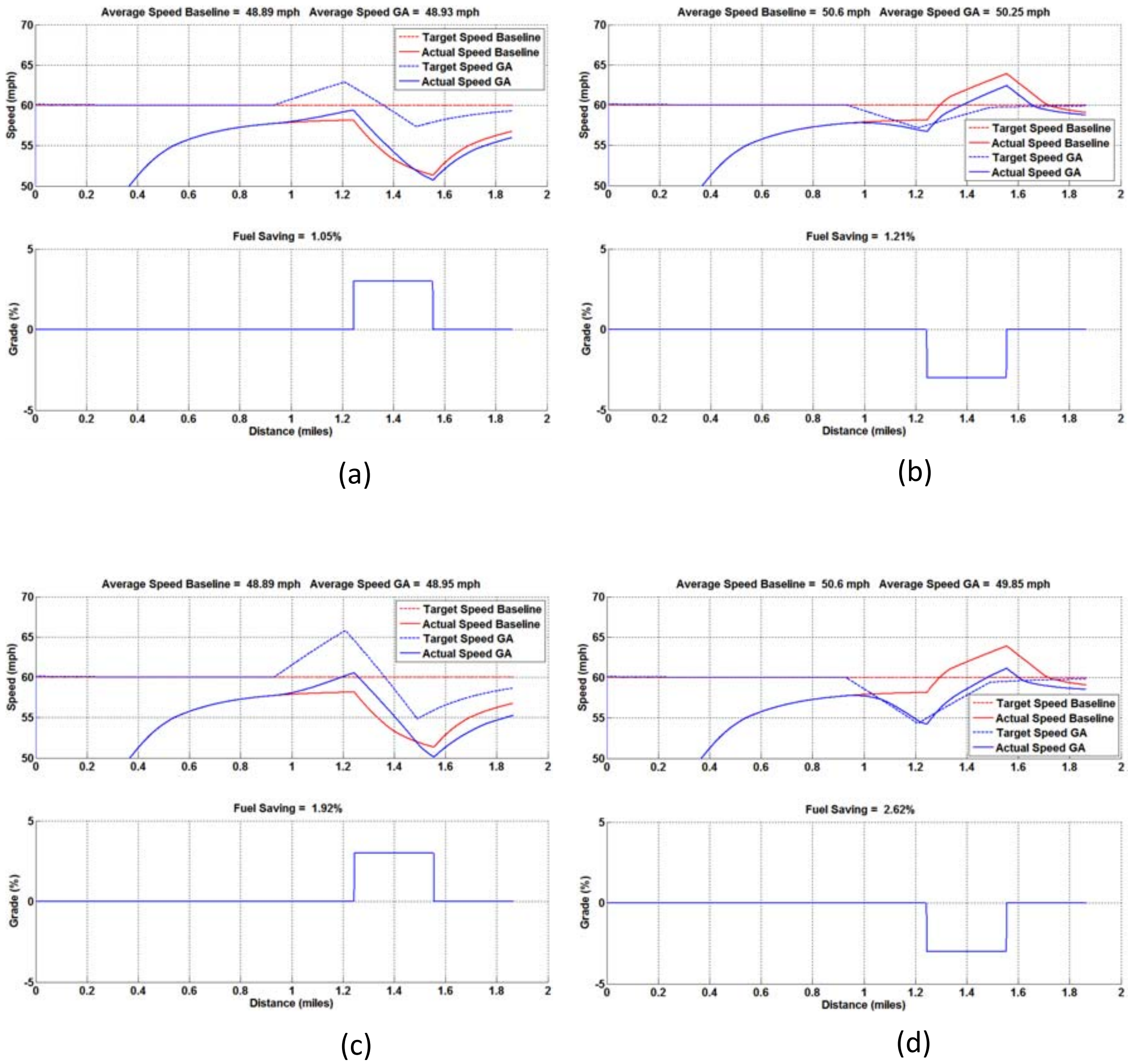


Figure 11: Results of Grade Adaptation for truck with heavy trailer: (a) Uphill with 5% speed variation, (b) Downhill with 5% speed variation, (c) Uphill with 10% speed variation, (d) Downhill with 10% speed variation

Table 6: Simulation results for Grade Adaptation

Scenario	Vehicle Weight (lbs)	Fuel saving with 5% speed variation (%)	Fuel saving with 10% speed variation (%)
Uphill	20,000	0.38	0.57
	70,000	1.05	1.92
Downhill	20,000	0.52	1.41
	70,000	1.21	2.62

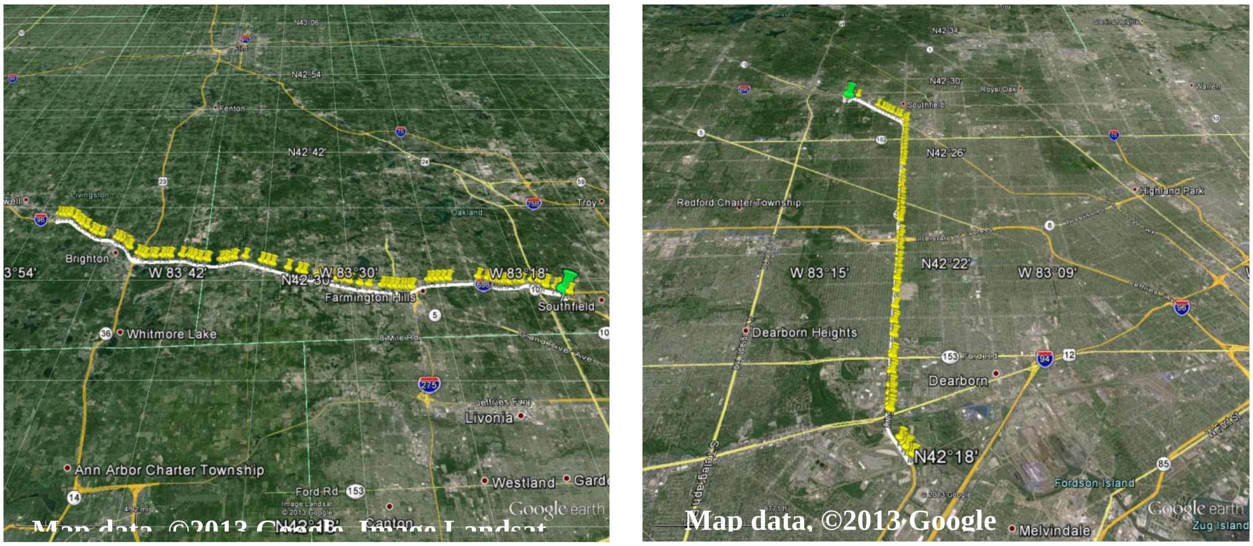


Figure 12: Test routes: Southfield-Howell (left) and Southfield-Allen Park (right)

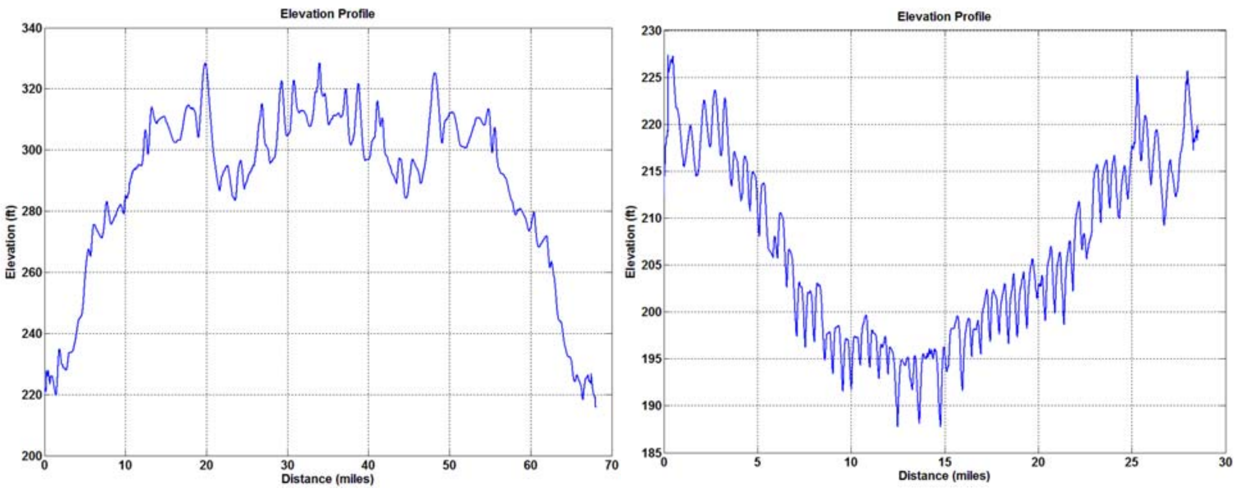


Figure 13: Elevation Profiles: Southfield-Howell (left) and Southfield-Allen Park (right)

Figure 14: Experimental truck

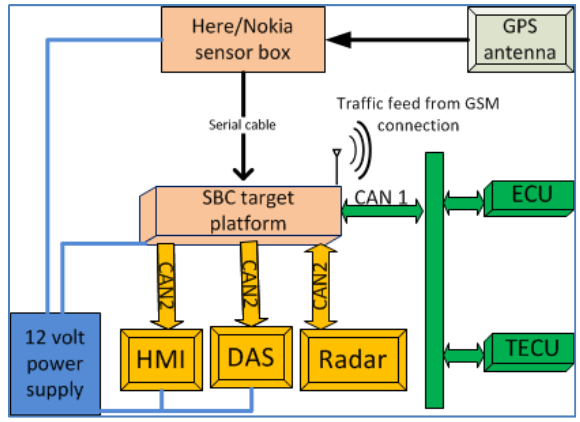


Figure 15: The system hardware setup

LPM controller implementation and Validation

The software architecture is composed of the following components: 1) LPM control software is compiled and built under Matlab/Simulink in the form of an executable program. The Vehicle Network Toolbox (VNT) is used to code the physical CAN interface through the USB port. Also VNT supports the virtual CAN communication that sets a direct dialogue between LPM code and ADASRP inside SBC. 2) LPM software uses Ethernet blocks from the Simulink library to receive the V2x. 3) Wireless Mobile Broadband data is sent through USB to ADASRP. 4) Vector CAN devices help to handle the data exchange from/to engine control (EECU), transmission control (TECU) as well as other CAN based devices. 5) Within the SBC a batch file is programmed to set the application launch sequence to run all the involved modules accordingly. For example, ADASRP needs to be initiated after the GPS signal becomes available. The LPM control software executable is not started until ADASRP program starts up and transmits information.

In order to validate the system, a class 8 heavy duty truck was equipped with the system. Two test routes, Southfield to Howell on I-696/96 and Southfield-Allen Park on M-39 Freeway, were selected as shown in Figure 12 with the corresponding elevation profile in Figure 13. Route from Southfield-Howell is 70 miles and route from Southfield-Allen Park is 30 miles. Each set of tests comprised of a baseline test, during which the system was turned off, and a system on test, on the same route and day to make sure the environmental conditions are approximately the same. Care was taken to warm up the truck before beginning any testing. The J1939 fuel flow signal was utilized to analyze the fuel consumption. An experienced driver, with over 20 years of driving experience, was used for these tests. In total, around 350 miles of truck driving data was collected during the testing which lasted 5 days. This driver can be expected to drive efficiently when the system is turned off so that the baseline drive is not biased.

Initial validation results

To analyze the benefit of the system, data from system on and system off cases are compared against each other. Any stretch of data that involves braking or traffic following, in one of the test drives, is disregarded. Furthermore, only those stretches are considered for comparison where the speed difference is small (Table 7). Grade data is then analyzed to look for uphill and downhill scenarios. The predictive grade data obtained from ADASRP is compared against the grade data reported by a grade sensor built into an Eaton® transmission to ensure the accuracy. Figure 16 shows the measured grade versus predictive grade. It can be observed that the predictive grade closely follows the measured grade.

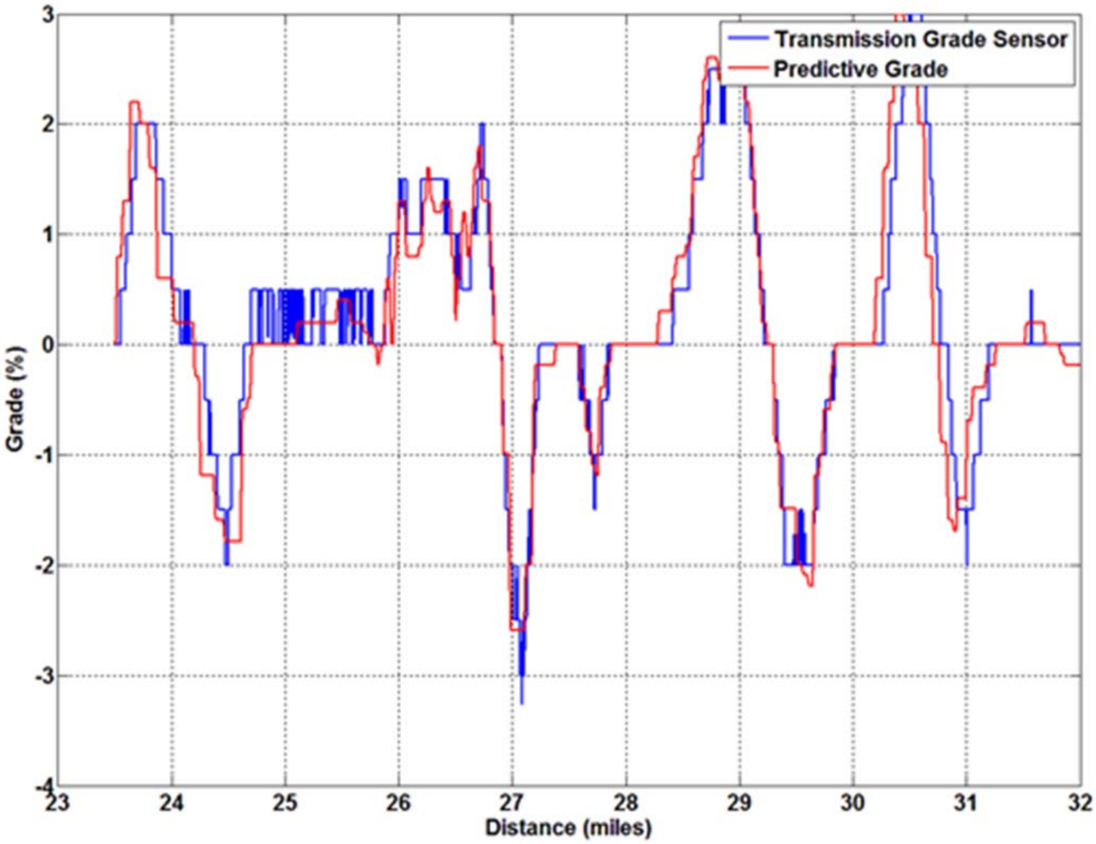


Figure 16: Predictive versus measured grade data

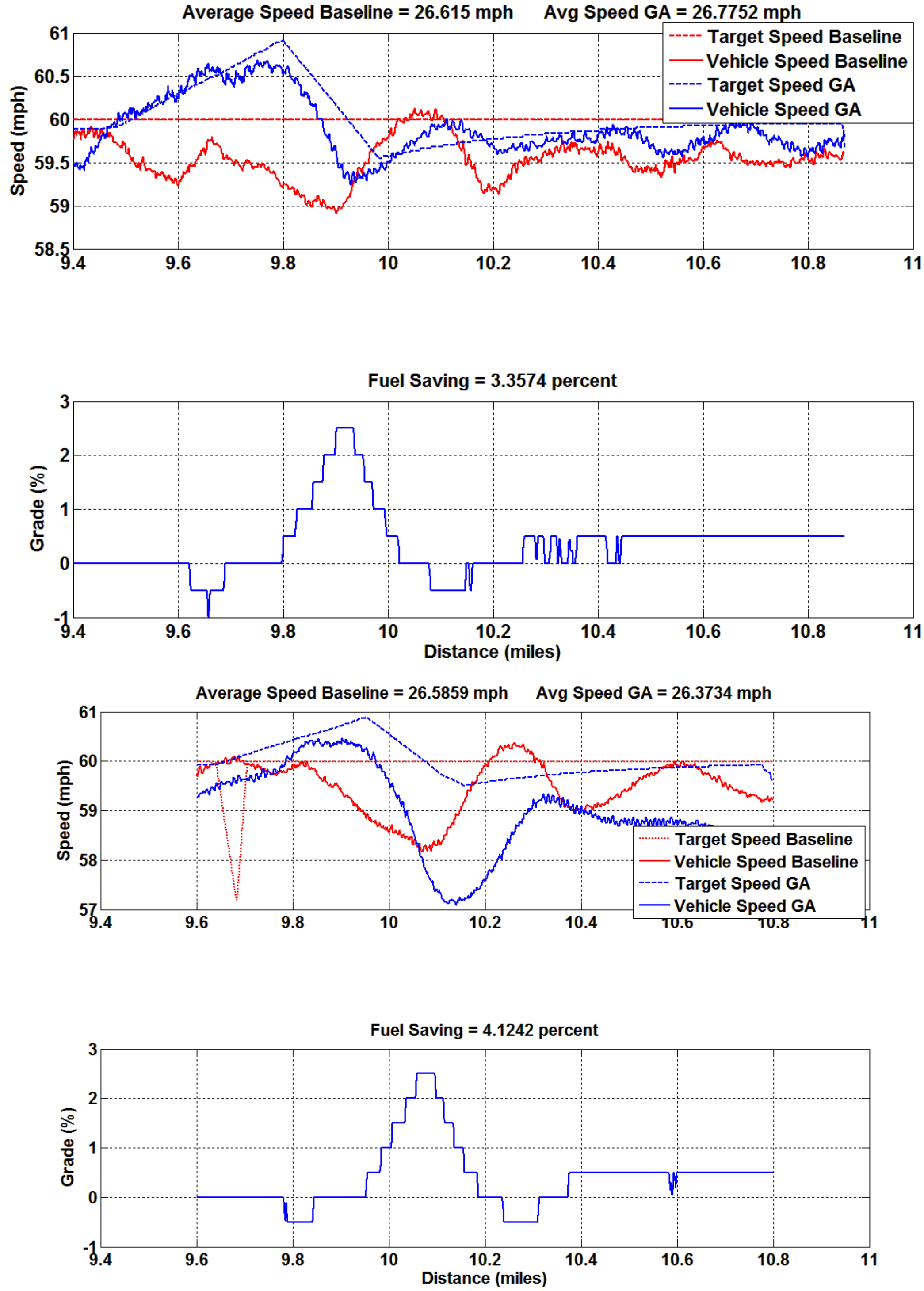


Figure 17: Grade adaptation on an uphill: without trailer (left), with heavy trailer (right)

Figure 17 to Figure 19 show the experimental results of grade adaptation. Tests were carried out on the routes mentioned above. The figures show only a portion of the entire data where no braking, gear shifting, traffic following or overtaking was observed for both system on and system off case. The target speed is the desired speed that the vehicle should follow to gain maximum fuel economy benefit. A controller is employed to follow the target speed.

For an uphill (Figure 17 (a) and (b)), the target speed is increased up to the point of reaching the uphill, i.e. at approx. 9.8 miles and 9.95 miles for Figure 17 (a) and (b) respectively. During the uphill the speed of the vehicle reduced as expected. Upon completion of the uphill, the speed is brought back to the reference speed. As suggested by the simulations, this strategy results in a fuel saving of 3.3% in the case without trailer and 4.1% in the case with trailer. This fuel saving is apparent due to the fact that by accelerating the vehicle before an uphill, the engine is operated in its efficient operational region. In addition, even more fuel saving is feasible due to the delay in shifting to lower gear due to speeding up before an uphill.

Similarly, for a downhill (Figure 18 (a) and (b)), the target speed is reduced before the start of downhill, at approx. 20.02 and 65.67 miles for figures (a) and (b) respectively. Furthermore, along the downhill the speed of the vehicle is allowed to increase and reach the reference speed until the end of the downhill. The increase in vehicle velocity is entirely with the aid of the down slope without any increase in throttle or need of braking, saving fuel both before the downhill as well as along it.

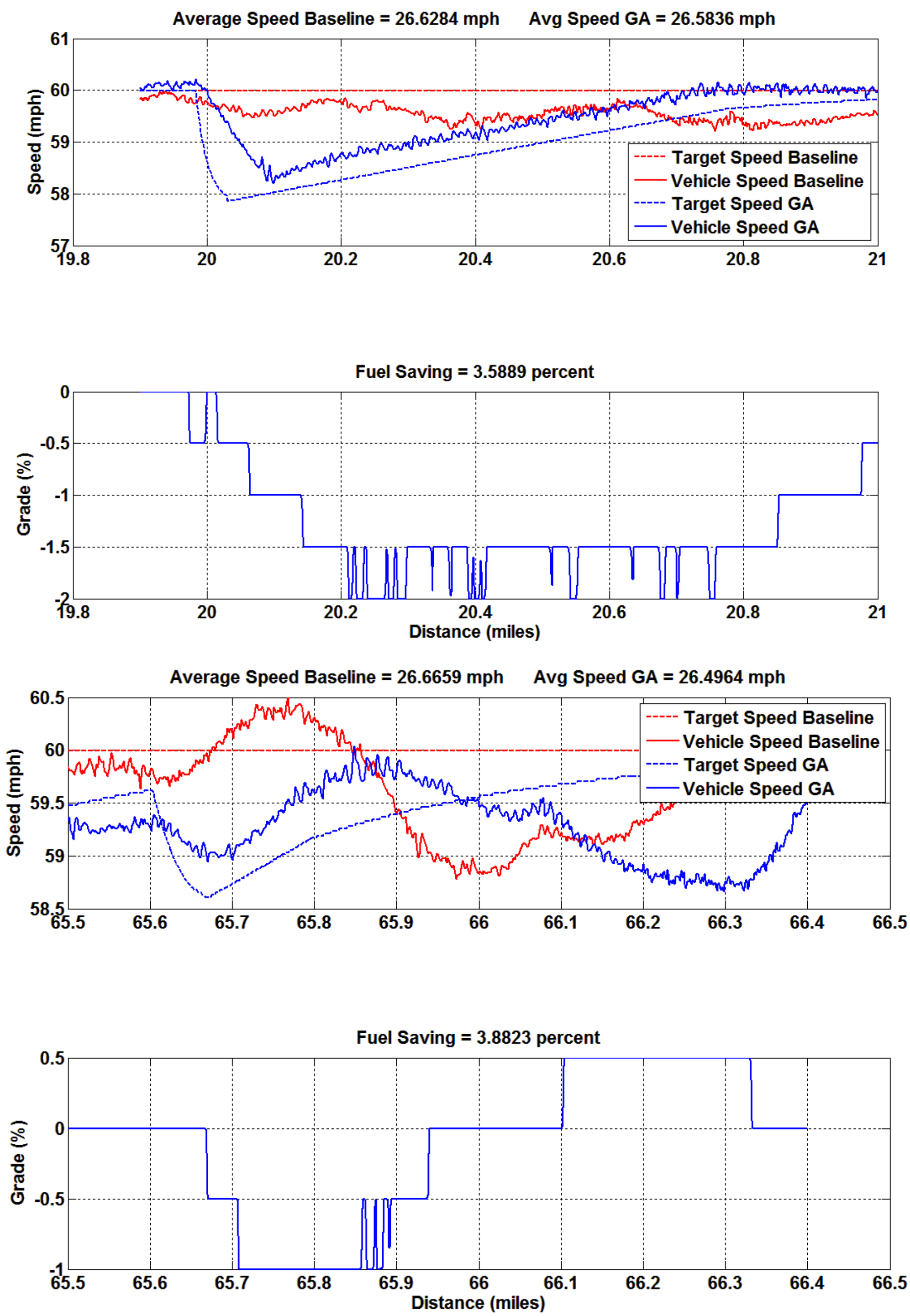


Figure 18: Grade adaptation on a downhill: without trailer (left), with heavy trailer (right)

Figure 19 (a) and (b) show the benefit of grade adaptation when there is a combination of both uphill and downhill. The same logic of increase/decrease of velocity before an uphill/downhill applies here as well.

It can be seen that the target speed following in case of the truck with heavy trailer is poor as compared to the truck without trailer for all the cases. This can be overcome by increasing the controller gains, however, this will also result in a more aggressive controller resulting in lower fuel saving.

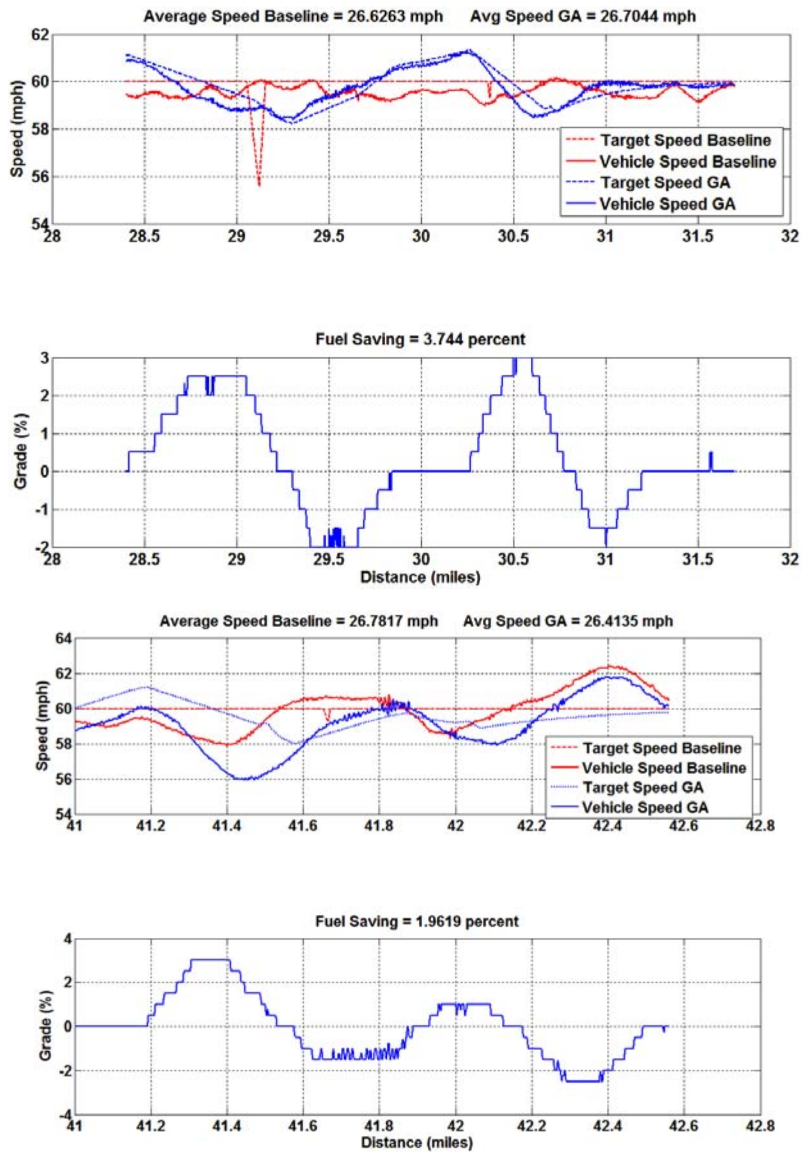


Figure 19: Grade adaptation on combination of uphills and downhills: without trailer (left), with heavy trailer (right)

Table 7 below shows a summary of the combined results for the various tests conducted. An overall fuel economy benefit of about 1.9% is seen in case of no trailer attached to the vehicle, whereas an improvement of 4.1% is seen for a heavy trailer case. The fuel saving trend matches the trend suggested from the simulations. Higher fuel savings is noted for the heavy vehicle when compared to the vehicle without trailer. Due to poor following of the target speed for the truck with a heavy trailer, a higher difference in speeds is seen between the baseline speed and the grade adapted speed (also shown in Table 7), the average speed being lower in case of grade adaptation. Moving with a lower average speed also contributes to fuel saving in case of truck with heavy trailer. This also contributes to higher fuel saving for this case. For these tests, the allowable variation in speed due to grade adaptation is set at 5% of the speed limit. The simulation results indicate that increasing this variation of target speed in the speed band of 10% will improve the fuel economy further. This remains to be tested and is the scope of future testing.

Table 7: Results from GA validation

Trailer	**Distance travelled with GA ON (% of total distance travelled)**	**Difference in speeds (m/s)**	**Gain in FE (%)**
No (20,000 lb)	28.2	-0.02	1.9
Heavy (70,000 lb)	19.2	-0.4	4.1

Subtask 3.2 – Human-machine interface development

Subtask 3.2.1 – Scope out interface concepts - identify possible displays based on scenario-specific analysis

In this task, eco-driving interface concepts used in other eco-driving systems were surveyed. The most effective systems feature simple displays that focus on acceleration/deceleration intensity or throttle use. They employ simple horizontal bar graph displays.

Key interactive requirements of the LPM system were identified and include:

- Indication to the driver when active intervention of the LPM is occurring. This distinguishes three states: LPM Inactive, Transitioning, and LPM Active. Interface concepts included using a color-coded border that changed in color and brightness, accompanied by sound to indicate LPM transitions.
- Presentation of advisory information to drivers. This includes:

- Throttle liftoff in anticipation of stopping or slowing down. The DVI advises drivers when to lift their foot off the accelerator. Interface concepts included use of a coordinated timing warning signal, followed by a "lift" command and simple verbal/visual commands to prepare and request a throttle liftoff.
- Throttle application (up or down) in anticipation of grades or turns. The DVI advises drivers whether the throttle application is too high or too low. Interface concepts included a bar graph display to advise about throttle control, indicating desired throttle control location and warnings related to transitions above and below this area. Alternative interfaces include verbal/visual indicators requesting more or less throttle.
- Transmission shift advice—the DVI advises drivers to shift up or down. This interface involves requests and display a higher or low gears.

- Signal phase information display. The DVI displays to drivers the current position in the signal phase. Interface concepts include a bar-graph depicting the final 10 seconds of a signal phase (red/green) the relative time remaining in the 10-second interval.
- Candidate interface concepts were defined and presented at the program review.

Subtask 3.2.2 - Develop simulation-based display hardware

- The vehicle simulator, located at UMTRI, was enhanced to interact with HMI through the acquisition of interface development application, Altia Design. This application allows the implementation of animated displays that can be controlled directly from simulator model outputs in software.

- A 7-inch VGA-based touch screen display (Model ALCDP7VGATS) was procured. Integration with driving simulator has been verified (see Figure 20).

Figure 20: VGA based, 7in display for HMI simulator study

Subtask 3.2.3 - Design simulator study

A report on the design of simulator study was submitted to DoE in 2012 [15]. A brief overview of the report is presented below.

The purpose of this simulator study was to test some fuel-economy display concepts in a simulator study. The study development timeline is planned to occur over the last quarter of 2012. During this time, a display interface that illustrates a few of the interactive functions required by Eaton's Look-ahead Driver Feedback and Powertrain Management control Module (LPM) for heavy trucks was developed.

The LPM's activity is dependent on some external conditions that the driver may also be aware of, and some internal conditions, that the driver may *not* be aware of. In order to make the internal state of the LPM known to the driver, Eaton has implemented a 3-level display that indicates the system internal operational state. It is **not** the purpose of the simulator study to emulate the specific LPM functions, since these functions are under development and are subject to many unknown real-world conditions. (For example, we do not know how "spotty" the mapping data may be, and thus are unable to predict how often the system slips between operational states.)

Simulator Testing of Interactive Components

Two candidate interfaces will be evaluated for each of the three interactive advisory functions described previously. The advisory functions will be tested under three simulator conditions:

1. Driver compliance with the advisory, when following a forward vehicle (usability).
2. Driver response to an unexpected braking event, when following a lead vehicle and complying with the advisory.
3. Driver compliance with the advisory when no forward vehicle is present (baseline usability).

For interactive component testing, a simple limited-access 2-lane roadway should suffice such that prototype interfaces for each interactive function can be tested within the same session block. The order of each of the three test conditions should be randomized (within each interface candidate presentation) and counterbalanced. Each candidate interface should be measured twice in each condition. An example session trial organization is provided for the three throttle lift candidate interfaces in Table 8 below. Trial presentation order would be shuffled within shaded blocks (i.e., within interface groups), and order of interface presentations would be counterbalanced across subjects (to counteract order effects). Finally order of functional component (i.e., throttle lift, throttle application, and transmission advice) presentation session would be counterbalanced across subjects.

Table 8: Example block organization of testing two throttle lift interfaces

Trial	Interface	Simulator Condition	Replication
1	1	1	1
2	1	2	1
3	1	3	1
4	1	1	2
5	1	2	2
6	1	3	2
7	2	1	1
8	2	2	1
9	2	3	1
10	2	1	2
11	2	2	2
12	2	3	2

If two examples of each of the three interface functions are tested, a total of 36 simulator trials will be required (2 replications * 2 versions * 3 simulator conditions * 3 functions).

Measured Data

Usability measures will be specific to the particular advisory message. These will include:

- Delay between the delivery of advice and the driver's response to that advice.
- The time it takes the driver to accomplish the advisory task to a defined criteria.

Driver performance measures will include:

- Response to an unexpected braking event by the forward vehicle. This measure would include the minimum TTC around the lead vehicle braking event, and driver reaction time to initiate braking (i.e., the delay between the lead vehicle braking and the subject vehicle's application of braking).

- Lane tracking quality while an interactive advisory is active. This measure may be based on the standard deviation of lane position within fixed time windows, or a frequency power analysis of steering performance (i.e., higher frequency)

Simulator Evaluation of Informational Components

Three informational interfaces that are currently anticipated include:

1. Scenario detection display. When the LPM recognizes a particular intervention scenario, this will be signified by either a displayed icon or message on the display interface. (The interface design may reserve different display screen regions to indicate scenario detection; variations may include different icon choices or messages.)
2. LPM activation status.
3. SPaT information display. This may also be depicted in a reserved screen region.

Evaluation of these display concepts will be performed by soliciting the subjective opinions of drivers using questionnaires. For these evaluations, the simulator only needs to establish a driving context while the various versions of the informational displays are demonstrated. For the first two, no specific features of the simulator work are particularly required—the driver is evaluating the displays based on legibility, understandability, and preference.

The SPaT demonstration, however, requires an approach to an intersection.

Example Simulator Algorithm: One possible scenario would be to cue a countdown timer as a JavaScript procedure executed as a one-second time trigger:

- A vehicle passes over a section of roadway preceding a signalized intersection (by about 300 meters). The intersection may be either red or green when the location trigger is tripped.
- The Altia-based SPaT display interface is activated, and the signal phase is identified (red/green)
- Time-based trigger is started which counts down from 15 each second.
- Each count, the SPaT display receives 2 pieces of information from the JavaScript: a signal state (red or green), and the current seconds remaining (integer) in the phase.
- When the countdown reaches zero, the signal light is commanded to transition to the next state.
- A position trigger located on the road past the traffic signal can be used to send a disable display command to the Altia interface.

Task 4.0 - System Finalization on a Prototype Vehicle

Table 9: Task 4 Activities

Task Name	Start	Finish
Task 4: System Finalization on a Prototype Vehicle	**Tue 1/15/13**	**Fri 2/28/14**
4.1 Perform driving simulator study and down select Human-to-machine Interface	**Tue 1/15/13**	**Fri 6/28/13**
Program designed simulator study on driving simulator	Mon 4/29/13	Mon 4/29/13
Completion of human subject testing in the UMTRI driving simulator	Mon 4/29/13	Wed 5/15/13
Driving Simulator experiment report documenting the test, test results and insights relevant to the project	Mon 4/1/13	Fri 6/28/13
4.2 Finalize Human-to-machine Interface Algorithm and Hardware Development	**Tue 1/15/13**	**Fri 6/28/13**
Selection of in-vehicle display	Tue 1/15/13	Tue 4/30/13
Finalize the interface between HMI and LAFE SW	Tue 4/30/13	Fri 5/31/13
Programming the display scenarios	Tue 4/30/13	Fri 6/28/13
HMI display: functional and technical interface document	Tue 4/30/13	Fri 6/28/13
4.3 System Integration and Validation on the Prototype Vehicle	**Tue 1/15/13**	**Fri 2/28/14**
Identify the prototype vehicle and obtain required agreements for project use in phase II	Tue 1/15/13	Tue 4/30/13
DAS data dictionary, including signals from the LAFE and other inputs	Tue 1/15/13	Fri 5/31/13
DAS , HMI, LAFE and other equipment integrated onto the prototype vehicle	Wed 7/31/13	Wed 7/31/13
Feedback received from team driver exposed to the prototype system	Thu 8/1/13	Fri 2/14/14
Summary of the system functionality validation results from the prototype vehicle	Tue 6/4/13	Fri 2/28/14

Deliverables: Driving Simulator Experiment Report (UMTRI)

Subtask 4.1: Perform driving simulator study and down select Human-to-machine interface

A report on the design of simulator study was submitted to DoE in 2012 [15]. A brief overview of the report is presented below.

Candidate interface components for a Look-ahead Powertrain Manager (LPM) were studied in a simulator study developed to collect subjective opinion and objective performance data. The study was conducted with the participation of 16 commercial vehicle drivers holding CDL licenses with Group A designation. For each display function, two alternative displays were shown to drivers. Performance measures were obtained for advisory functions that included driver compliance with the advisories and the driver's ability to react to forward vehicle braking. The advisory functions examined included throttle advice and gear selection advice.

This simulator study investigated alternative driver-vehicle-interface (DVI) concepts for the Look-ahead Powertrain Monitor (LPM). This system shares control of the vehicle throttle with the driver, advising the driver about who (driver or LPM) is currently in control of the vehicle. The system may provide interactive advice to the driver about throttle use and advice about transmission gear selection. In addition, the LPM may provide informational display to the driver that identifies upcoming road information based on various sensors.

The purpose of the simulator study is to examine each of these display functions separately, using alternative displays to determine which alternative is subjectively preferred by drivers; is believed to be the easiest to use, least distracting, and requires fewest off-road glances. For the advisory functions, throttle advice and gear selection advice, objective performance measures were also collected in various simulator scenarios.

Simulator Procedure

Subjects. Sixteen commercial truck drivers holding current CDL licenses with Group A designations were recruited to participate in the simulator study. Drivers with a reported susceptibility for motion sickness were excluded from the study. Driver recruitment was conducted though general internet postings for truck drivers, direct referrals from participating drivers, and from instructional staff at commercial driver training schools in the local Ann Arbor area.

Procedure. The simulator session investigated the throttle advisory and gear advisory display components first, before proceeding to obtain subjective evaluation of the informational display components. Presentation order of the throttle and gear advisory scenarios were counterbalanced across subjects to reduce the potential for practice effects to bias performance. Within each advisory condition, interface order was similarly counterbalanced so that each of the two presented candidate interfaces were presented first or second the same number of times across subjects. Performance and compliance measures were collected for the advisory display components.

Three driving scenarios were presented to drivers in the simulator. The presentation order was randomized. Each scenario was presented twice within a block dedicated to each of the two candidate display interfaces. For each advisory display there were 6 trials, making a total of 12 trials within a single simulator run. The three trial scenarios were: a) free driving along a rural roadway with no other vehicles present, b) driving behind another lead vehicle programmed to maintain a railway time of about 6 seconds, and c) driving behind a lead vehicle programmed to initially maintain a tailway time of 6 seconds, but randomly changing this to 2 seconds at an unpredictable point in time. This latter condition resulted in a forward vehicle unexpectedly slowing significantly at an unpredictable point in time. In this last trial, performance measures were obtained measuring the time from the lead vehicle brake application to the participant’s application of the brake in the following vehicle, and the minimum headway time to the forward vehicle at the time of the forward vehicle brake application.

Compliance measures were also recorded during each of the three driving scenarios, when the throttle or gear advisory was initially presented. In each scenario, the advisory was presented after about 5 seconds of driving. In the throttle advisory condition, the throttle advisory interface was displayed for about 10 seconds. Compliance was measured as the percent of time the driver maintained the throttle within the requested range over the presentation of the advisory. For the gear selection advisory, compliance was measured as the time between delivery of the advisory, and the driver’s selection of the transmission gear.

For the informational display components, simple demonstrations were provided to illustrate functions. In the signal phase and timing displays, participants drove through an urban roadway, encountering traffic lights at each intersection. Within the simulator vehicle, alternative SPaT displays showed the current phase and remaining timing for the signal phase. For the road scenario informational display and the LPM state informational display, a static in-vehicle demonstration of each display condition was provided.

Subjective Questionnaires. After each component was demonstrated, participants were asked to complete a questionnaire that asked them to choose which of the two candidate displays the participant preferred in several evaluation decisions. Participants were also invited to comment on each display alternative.

The evaluation decisions included:

- Which display is easiest to understand?
- Which display is least distracting?
- Which display requires fewer off-road glances?
- Which display do you prefer?

Subtask 4.2: Finalize HMI algorithm and hardware development (UMTRI)

In-Vehicle Display Hardware

UMTRI purchased and installed a physical display device in the Phase II test-bed tractor in early summer. This was an off-the-shelf ruggedized industrial display that can withstand the harsh environment expected in a commercial truck as well as provide suitable performance within a wide range of temperature and light conditions. However, the display was a critical element of the whole system as this is the only hardware that is visible to the fleet and the drivers. In order to obtain fleet manager approval at the design stage, Con-way Freight fleet representatives were invited to look at the setup and provide their feedback. The fleet manager recommended that a display with a different form factor (size) be utilized for the study. Therefore UMTRI designed and fabricated two of its own displays for use in the Phase III pilot test plan using a COTS LCD and COTS display interface hardware. These displays include automatic adjustment for ambient illumination, and were completed and bench tested during the final quarter of Phase II.

Interface Algorithm

The HMI interface was finalized and documented in a report titled “The Human Machine Interface Functional Description and Technical Specification” which describes the full set of the design specifications. This report was delivered to DoE. This report was a collaborative UMTRI/Eaton effort and describes the physical elements of the display as well as the Eaton LPM CAN messages used to drive the interface. The Data Acquisition System (DAS) and the HMI also broadcast health messages back to the LPM, to ensure that the DAS/HMI are functioning and the display is showing messages to the driver. The display functionality was verified on the Phase II test-bed tractor.

Subtask 4.3: System integration and validation on the prototype vehicle

A report on the design of the simulator study was submitted to DoE in 2013 [16]. A brief overview of the report is presented below.

The Phase II LPM and an UMTRI data acquisition system (DAS) were integrated on an UMTRI-owned 2006 International Transtar 8600 with an automatically shifted transmission; see Figure 21. There was some delay due to the replacement of the existing transmission with a newer Ultrashift Plus unit that can support the capabilities needed in this study. This replacement was required since the old transmission was inappropriate for modification of its electronic control unit (TECU) code that was required to receive control messages from the LPM controller. Eaton provided a new Ultrashift Plus transmission at no cost, to be utilized for the successful completion of the project. The existing transmission was replaced and the transmission control unit (TECU) code was reprogrammed to work with LPM controller.

Figure 21: Views of the Phase II prototype vehicle with DAS components

DAS, HMI, LAFE and other equipment were integrated onto the prototype vehicle: Figure 22 (Left) shows the data acquisition system that is being used in the vehicle. Figure 22 (right) shows the Single Board Computer (SBC) that will host the look-ahead Fusion Engine. The HMI display has been mounted on the dashboard.

The initial SBC that was selected for this project was based on the computational load of 3D map software as well as the LPM executable. During the course of this project, an upgrade of the 3D map software as well as development of LPM executable that upgraded some of the previous features as well as added a number of additional features increased the computational performance requirement of the embedded target (SBC). This forced a hardware upgrade. The SBC was upgraded to a more powerful, multicore CPU with additional RAM. It was further tested to confirm the computational capability to host all the required software in both lab and on the truck. The complete system was integrated on the test vehicle.

During the initial testing of the system, a number of unexpected bugs were discovered. These bugs were identified and resolved. In addition, an upgrade was required to the 3D map software and changes were required on the LAFE software build.

Figure 22: Data acquition system (left) and Single board computer (right)

Feedback received from the driver who drove the trucks was incorporated in the system in the form of additional features or refinement of the existing features. This includes:

1. Drivers need a way to override the system: The drivers felt that they need a way to override the system in case they need temporary control. Driver override functionality was introduced in the system. An override hardware switch (Figure 23) was introduced and tested.

Figure 23: Driver override switch

2. System should be made more rugged to environmental noise: There were a few instances in the initial testing when the hardware malfunctioned due to noise in the truck environment. An enclosure (Figure 24) was introduced that packages the system neatly and protects it against the environment, while making it rugged.

Figure 24: System enclosure

3. NavTeq box failed once: NavTeq sensor box (Figure 25 (a)) was being used as a gateway between GPS sensor and ADASRP software. The functionality of this box is to provide the positioning data in NMEA protocol as well as to provide dead reckoning in the case

when GPS data is not available. However, this box is research hardware and is not meant for production. We noticed a failure in this device that may be related to a harsh climate. A replacement was found and tested (Figure 25 (b)). This GPS is a production device and performed well on the trucks without field failure.

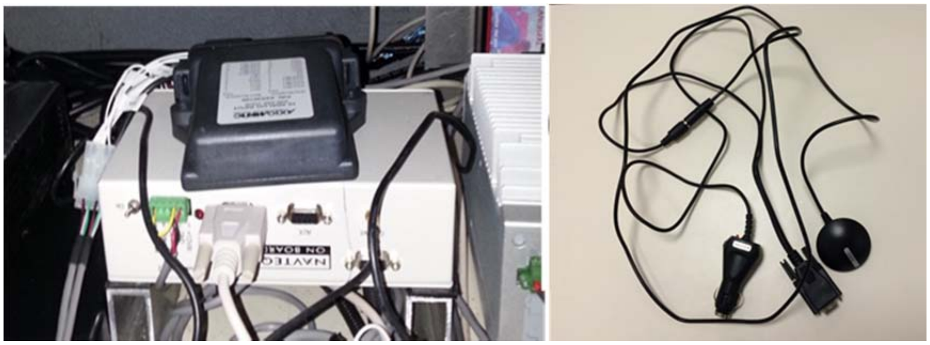


Figure 25: (a) NavTeq Sensorbox (left), (b) replacement

4. Message/signal refinement in DAS: Refinements to CAN messages and signals were carried out.
5. System robustness and safety features added: Various features were added to the base LPM code to make it more robust and integrate it with the TECU, DAS and HMI software. These changes are:
    a. Added HMI, DAS and LPM heartbeat signal. If one of these components malfunctions, the heartbeat signal will be interrupted and the functionality of the whole system will be disabled along with an i message to the driver. This is to maintain driver safety.
    b. In case of system failure, TECU will take over and limit the vehicle to the fleet policy speed. TECU will also limit the acceleration in case it detects a sudden failure of the system.
6. Driver feedback on the HMI display: Various comments were received from the drivers about the information being displayed. These included comments about font size, icons etc. Changes have been made to accommodate these comments.

The system was validated in a field test conducted by UMTRI. The validation test plan is presented below.

LPM Validation Test Plan

A plan to validate LPM functionality on UMTRI vehicle was proposed in 2013. A brief overview of the report is presented below.

The following section lists the plans presented and executed by UMTRI to conduct on-road test of the prototype Eaton Look-Ahead Powertrain Management (LPM) system. The intent of the test is to:

- Get initial driver feedback on the LPM performance and DVI
- Evaluate the system robustness of the LPM, DAS and DVI by logging 24 hours of driving
- Evaluate LPM performance in terms of repeatability and functionality
- Evaluate LPM performance in terms of fuel savings
- Define and deliver a preliminary data set to ORNL for their analysis needs
- Define and deliver a data set to Eaton for their evaluation needs

The experimental design of the tests involves 4 drivers, two test periods (morning and afternoon) and two LPM system states (baseline and treatment). Each driver will drive the route twice for a given test period, once with the system disabled (baseline) and once with the LPM system enabled (treatment). Each driver will perform a morning and afternoon set of drives. All tests will be balanced across drivers, time of day, and system state. The general assumptions for the tests include:

- Single Route driven in the same direction for all tests
- Mixed road type: 64% Surface; 36% Limited Access Highway
- Same tractor and trailer combination is driven for all tests
- Single load for trailer (approximately the maximum load given the seasonal restriction for the Ann Arbor area)
- Single Fuel Batch for all tests
- Manual control only of the tractor (the driver will be instructed to not use cruise control)

The tests will be accompanied by a near-silent observer called the test conductor. This person will record any anomalous events related to either the LPM system or the traffic environment. These notes will be used later in the evaluation of the system performance and conduct of system validation tests. The test conductor will clarify any route questions by the driver. The test conductor will not explain the system performance to the driver, but will have the ability to verify that the system is working as designed.

A detailed schedule for the four drivers is given in Table 10. A total of 16 tests will be performed over a four day period. Test days will be selected based on weather conditions to minimize changes in temperature, precipitation, and wind conditions during the morning or afternoon test periods.

Detailed Experimental Design and Test Route Specifics

The test route is shown in Figure 26. The route is 57 miles long and is expected to take approximately 1.5 hours to drive. The route is 64% surface streets and 36% limited access highways. This blend of road-type was selected to approximately mirror the overall exposure of Con-way Pick-up and Delivery (P&D) drivers which had an overall exposure of 72% surface and 28% limited access highway during the UMTRI/Eaton IVBSS Heavy Truck field test. Route waypoints, road type, and distance are summarized in Table 11. The table also shows the total distance and percent surface/highway for this route (UMTRI) and Con-way P&D exposure. Route instructions for the driver are given in Figure 27.

Table 10: Driver Schedule for On-road tests with time-of-day and LPM State conditions

Driver	Day Number	Trip Number	Trip TOD	LPM State
A	1	1	9 to 10:30 am	Baseline
A	1	2	10:30 to 12 pm	Treatment
B	1	3	1 to 2:30 pm	Treatment
B	1	4	2:30 to 4 pm	Baseline
B	2	5	9 to 10:30 am	Baseline
B	2	6	10:30 to 12 pm	Treatment
A	2	7	1 to 2:30 pm	Treatment
A	2	8	2:30 to 4 pm	Baseline
C	3	9	9 to 10:30 am	Treatment
C	3	10	10:30 to 12 pm	Baseline
D	3	11	1 to 2:30 pm	Baseline
D	3	12	2:30 to 4 pm	Treatment
D	4	13	9 to 10:30 am	Treatment
D	4	14	10:30 to 12 pm	Baseline
C	4	15	1 to 2:30 pm	Baseline
C	4	16	2:30 to 4 pm	Treatment

Table 11: Route Waypoint, Road type and Distance

Waypoint	Road Type	Distance, miles
A	Surface	8.3
B	Surface	6.8
C	Highway	13.7
D	Surface	11.2
E	Highway	3.1
F	Surface	2.4
G	Surface	2.5
H	Surface	4
I	Highway	3.5
J	Surface	1.6
	Total	57.1
UMTRI	Surface	64%
	Highway	36%
Conway P&D	Surface	72%
	Highway	28%

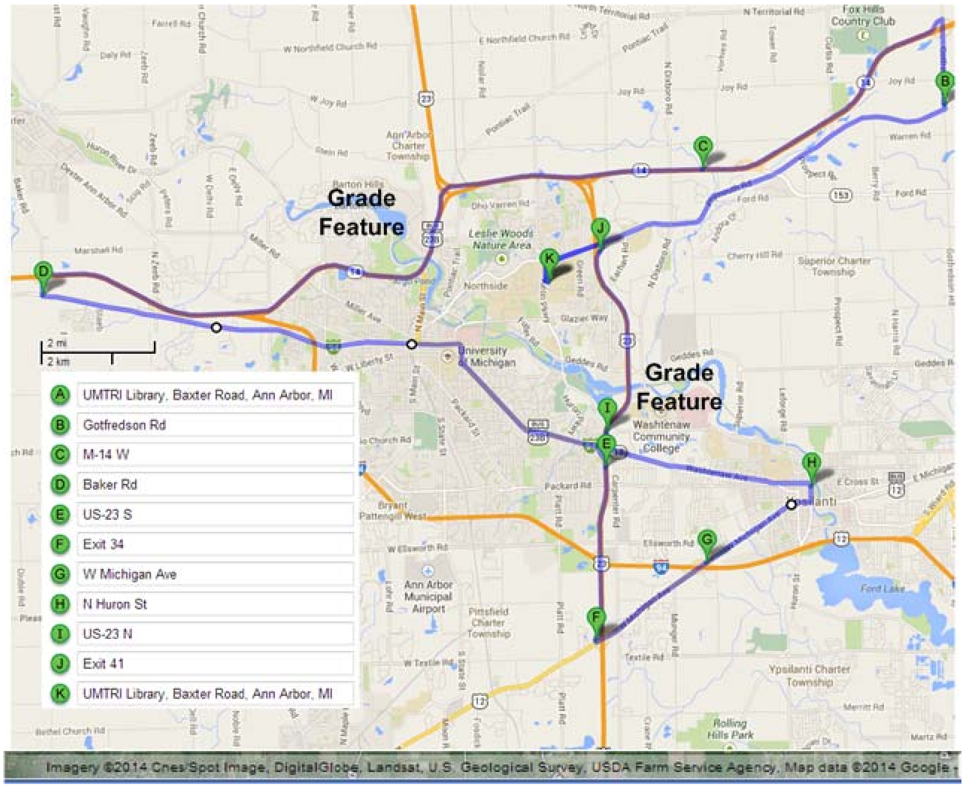
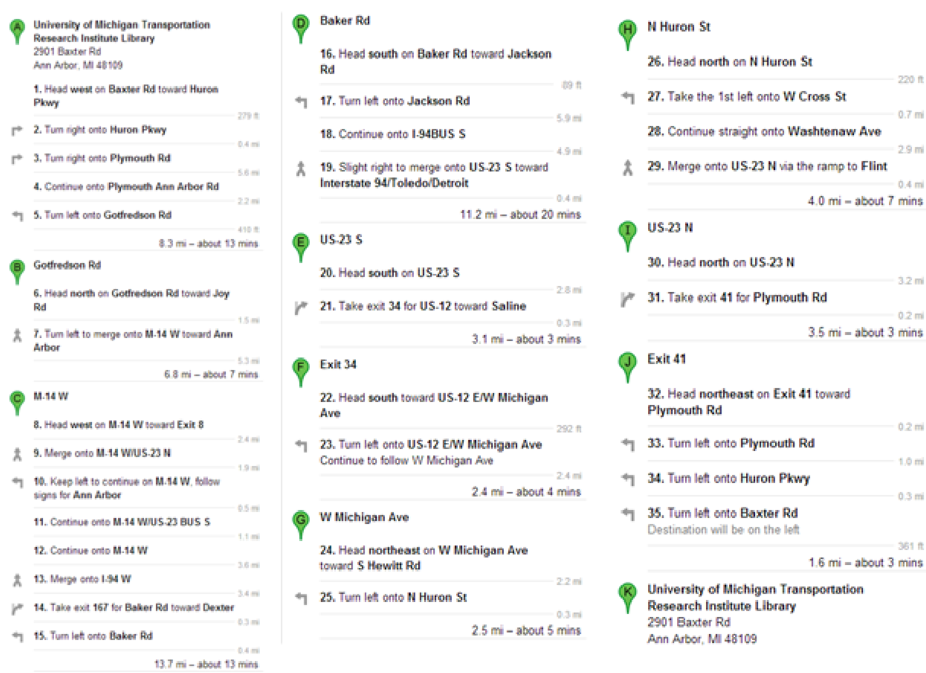


Figure 26: Test route for on-road LPM evaluation test



A University of Michigan Transportation Research Institute Library
2901 Baxter Rd
Ann Arbor, MI 48109

1. Head west on Baxter Rd toward Huron Pkwy — 279 ft
2. Turn right onto Huron Pkwy — 0.4 mi
3. Turn right onto Plymouth Rd — 5.6 mi
4. Continue onto Plymouth Ann Arbor Rd — 2.2 mi
5. Turn left onto Gotfredson Rd — 410 ft

8.3 mi – about 13 mins

B Gotfredson Rd

6. Head north on Gotfredson Rd toward Joy Rd — 1.5 mi
7. Turn left to merge onto M-14 W toward Ann Arbor — 5.3 mi

6.8 mi – about 7 mins

C M-14 W

8. Head west on M-14 W toward Exit 8 — 2.4 mi
9. Merge onto M-14 W/US-23 N — 1.9 mi
10. Keep left to continue on M-14 W, follow signs for Ann Arbor — 0.5 mi
11. Continue onto M-14 W/US-23 BUS S — 1.1 mi
12. Continue onto M-14 W — 3.6 mi
13. Merge onto I-94 W — 3.4 mi
14. Take exit 167 for Baker Rd toward Dexter — 0.3 mi
15. Turn left onto Baker Rd — 0.4 mi

13.7 mi – about 13 mins

D Baker Rd

16. Head south on Baker Rd toward Jackson Rd — 69 ft
17. Turn left onto Jackson Rd — 5.9 mi
18. Continue onto I-94BUS S — 4.9 mi
19. Slight right to merge onto US-23 S toward Interstate 94/Toledo/Detroit — 0.4 mi

11.2 mi – about 20 mins

E US-23 S

20. Head south on US-23 S — 2.8 mi
21. Take exit 34 for US-12 toward Saline — 0.3 mi

3.1 mi – about 3 mins

F Exit 34

22. Head south toward US-12 E/W Michigan Ave — 292 ft
23. Turn left onto US-12 E/W Michigan Ave Continue to follow W Michigan Ave — 2.4 mi

2.4 mi – about 4 mins

G W Michigan Ave

24. Head northeast on W Michigan Ave toward S Hewitt Rd — 2.2 mi
25. Turn left onto N Huron St — 0.3 mi

2.5 mi – about 5 mins

H N Huron St

26. Head north on N Huron St — 220 ft
27. Take the 1st left onto W Cross St — 0.7 mi
28. Continue straight onto Washtenaw Ave — 2.9 mi
29. Merge onto US-23 N via the ramp to Flint — 0.4 mi

4.0 mi – about 7 mins

I US-23 N

30. Head north on US-23 N — 3.2 mi
31. Take exit 41 for Plymouth Rd — 0.2 mi

3.5 mi – about 3 mins

J Exit 41

32. Head northeast on Exit 41 toward Plymouth Rd — 0.2 mi
33. Turn left onto Plymouth Rd — 1.0 mi
34. Turn left onto Huron Pkwy — 0.3 mi
35. Turn left onto Baxter Rd Destination will be on the left — 361 ft

1.6 mi – about 3 mins

K University of Michigan Transportation Research Institute Library
2901 Baxter Rd
Ann Arbor, MI 48109

Figure 27: Route Instructions for the driver

Procedures for Conducting the Tests

General items done before the first day of testing.

- Get scaled weight of the tractor and trailer per axle (Front, Tandem, Trailer Axle)
- Fill/check all auxiliary fluids (wiper, oil, coolant)

Start of Day Procedure:

- Tractor ignition off
- Tractor/Trailer connected, facing East against the high-bay wall of UMTRI (center of East High-bay doors)
- Check/Adjust all tire pressures to max rating
- Start tractor and let idle for 30 minutes until up to temperature
- Turn ignition off

General Driver Instructions include:

- Be familiar with route and drive as you would normally
- Ignore accompanied person (Test conductor)
- Manual driving only (No cruise control)
- Keep windows and quarter window vents closed
- No air conditioning
- No cell phone use
- No cussing
- No smoking

Pre-trip Driver to do List:

- Ignition off
- Fill and record auxiliary fuel tank weight
- Perform tractor/trailer pre-trip inspection
- Adjust seat, mirrors, steering wheel, seat belt
- Turn headlights on to low
- Set LPM State
- Start engine and immediately proceed to route obeying all traffic laws

Post-trip Driver to do List:

- Upon return to UMTRI, park in the same spot facing West, turn ignition off immediately
- Record auxiliary fuel tank weight
- Re-park tractor/trailer facing East between high-bay doors
- Tractor Ignition off

Validation Test Results

To summarize, the LPM system functionality was verified on the UMTRI prototype truck as per the functionality listed in the LPM functional specification document. The system was found to accomplish specifications listed in the functional specification document. A validation report was submitted to DoE [16].

Eaton Safety Certification

In addition to the system validation of the LPM system by UMTRI team, an Eaton team was assembled to carry out a detailed safety review of the LPM system. In this review, all possible failure modes were evaluated and addressed. The suggested safety measures included built in diagnostic in the LPM system that disables any driver override if a critical component failure is detected and modification of the TECU code to provide backup functionality in the situation of LPM system failure. Engineers from Eaton’s vehicle engineering group modified the TECU code and performed TECU safety certification before releasing a build to be utilized for the pilot test. This certification was carried out on HIL test setup at Eaton’s facility. Following the incorporation of all these features, a review of overall functionality of the system was carried out by an Eaton safety team. A test drive was conducted by UMTRI with Eaton certification team and the functionality was proved. The system was deemed fit for pilot test after the safety certification was carried out.

Task 5.0 - Pilot Test Planning

Table 12: Task 5 Activities

Task Name	Start	Finish
Task 5: Pilot Test Planning	**Thu 2/28/13**	**Wed 10/2/13**
5.1 Data Acquisition System build 1	**Thu 2/28/13**	**Wed 1/15/14**
UMTRI DAS fabricated for the Phase II prototype vehicle	Thu 2/28/13	Mon 7/1/13
DAS tested on bench	Thu 2/28/13	Thu 10/31/13
DAS test on integrated system	Thu 2/28/13	Wed 1/15/14
5.2 Pilot Test Planning	**Tue 1/15/13**	**Fri 3/21/14**
Secure commitment from a fleet for Phase III testing	Thu 8/15/13	Mon 9/30/13
Fuel consumption measurement plan for Phase III	Tue 1/15/13	Tue 4/30/13
Legal documents submitted to Con-way	Tue 1/15/13	Tue 12/31/13
Prepare test plan and documents for Phase III IRB submission	Tue 1/15/13	Fri 12/13/13
IRB committee review	Wed 1/1/14	Fri 2/7/14
CoC filing	Sat 2/1/14	Fri 2/14/14
CoC received	Fri 2/7/14	Fri 3/21/14
Legal documents in place	Fri 2/28/14	Fri 2/28/14
Complete BOM of system	Fri 3/1/13	Tue 12/31/13
Build enclosure for the system	Wed 1/1/14	Fri 2/14/14
5.3 Pilot Test Vehicle Preparation (I)	**Fri 3/1/13**	**Fri 3/14/14**
Complete the fabrication of two DAS systems for Phase III testing	Fri 3/1/13	Thu 2/13/14
Visit Con-way when the vehicle arrive and take measurements	Tue 12/31/13	Tue 12/31/13
Complete fabrication of 2 LAFE systems	**Mon 2/3/14**	**Fri 3/14/14**
Receive material for 2 complete BOM	Fri 2/28/14	Fri 3/14/14
Complete build and verify	Mon 2/3/14	Mon 2/3/14
Experiment test plan for Phase III field study	Fri 3/1/13	Thu 10/31/13
Test plan shared with Con-way	Fri 3/1/13	Thu 10/31/13
Finalize the test plan	Fri 1/31/14	Fri 1/31/14

Subtask 5.1: Data acquisition system (DAS) Build 1 (UMTRI)

A total of 3 DAS units were fabricated. The DAS are based on a design being used for 124 units in a large vehicle-to-vehicle study at UMTRI, with modifications for this project. The DAS will collect data from the OEM CAN bus (J1939) as well as the private CAN bus specific to the project. The DAS itself will have four video channels, yaw rate and acceleration sensors, and GPS.

Subtask 5.2: Pilot test planning (UMTRI, Eaton, ORNL)

Con-way agreed to be a participant in this project by making available 2 vehicles equipped with Eaton Ultrashift Plus transmissions in Phase III. The pilot test vehicles were delivered to Con-way in January 2014. A team from UMTRI and Eaton visited Con-way's Romulus facility in January 2014 to carry out initial measurements on the pilot vehicle.

A Fleet Trial Agreement was prepared jointly by Eaton, UMTRI and Con-way teams to enable working jointly on the pilot test. In addition, UMTRI and Con-way signed an indemnification document for UMTRI drivers to be able to drive Con-way vehicles. A face-to-face meeting was held with Con-way, UMTRI and Eaton on February 26, 2014 where all the legal documents were signed to carry out the pilot test.

A fuel consumption measurement and evaluation plan was formulated by ORNL. The approach was based on analysis of the J1939 data collected during the pilot test as well as simulation based approach that will leverage ORNL's experience in evaluation of large data sets from fleet trials. Possible addition of a fuel flow sensor, although not in the original scope of the work, was discussed by the team. After consideration of the cost associated with purchasing a new fuel flow sensor versus the achieved accuracy, a decision was made to utilize the existing J1939 fuel flow reading on the vehicles. A report on the fuel measurement plan was provided to DoE [17].

In order to conduct any testing that involves human subjects, UMTRI had to obtain permission from an internal Institutional Review Board (IRB). In addition, a Certificate of Confidentiality (CoC) from NIH was pursued in order to obtain protection on the data collected during the pilot test. However, NIMH refused to consider the application stating that this is a fuel efficiency study and it falls outside their mission. Since this is the sole organization that can provide a CoC, further perusal of CoC was not considered. The CoC application was denied in April first week and IRB approval was received in mid-May. The IRB approval was delayed due to multiple iterations of clarifications that the IRB council sought. The driver recruitment could not be initiated until IRB approval was received. The driver recruitment was finalized towards the end of June and the pilot test was launched in the first week of July.

Subtask 5.3: Pilot test vehicle preparation – Part 1(UMTRI, Eaton)

The build of Phase III DAS's was completed. Eaton and UMTRI visited the Con-way Freight terminal in order to take measurements of the new Freightliner Cascadia tractors that were special-ordered by Con-way for this project. In addition, the trucks were brought to UMTRI facility to take detailed measurements for brackets and hardware design. The fabrication of the hardware was started at UMTRI. The experimental test plan was finalized and shared with Con-way. The BOM for Eaton LPM system was finalized and parts for building 2 additional systems arrived at Eaton in Q1, 2014. The fabrication of these systems was started and expected to finish in Q2, 2014. As noted above, there was delay of 3 months in starting the pilot test due to the changes required on the system, the necessary rework, the validation and certification of the system as well as obtaining the required approvals.

Task 6.0 - Pilot Test

Table 13: Task 6 Activities

Task Name	Start	Finish
Task 6: Pilot Test	**Thu 1/2/14**	**Fri 10/31/14**
6.1 Pilot Test Vehicle Preparation (II)	**Thu 1/2/14**	**Fri 10/31/14**
Indemnification document in place	Thu 1/2/14	Tue 4/1/14
Vehicles arrive at UMTRI	Tue 4/1/14	Tue 4/1/14
System install and validation	Tue 4/1/14	Tue 4/15/14
driver recruitment	Sat 2/1/14	Wed 4/30/14
Driver training material ready	Thu 1/2/14	Fri 2/28/14
Driver training	Mon 4/7/14	Tue 9/30/14
Driver questionnaire ready	Fri 2/28/14	Mon 3/31/14
6.2 Pilot Test	**Mon 4/14/14**	**Fri 10/31/14**
Early data and test review	Mon 7/7/14	Fri 8/8/14
Data download and weekly visit	Mon 4/14/14	Fri 10/31/14
Maintenance	Mon 4/14/14	Fri 10/31/14

Subtask 6.1: Pilot test vehicle preparation

The indemnification document was signed between Con-way and UMTRI. Driver training material and driver questionnaire was finalized. The Con-way trucks were brought to UMTRI facility starting May 8 and the system installation was carried out. Figure 28 and Figure 29 below shows the system installation on Con-way tractor.

Figure 28: Con-way tractor installation

Figure 29: Con-way tractor sub-systems

Driver recruitment: Driver interest in pilot test participation was very high due to new tractors as well as automated transmissions. The drivers were finalized towards the end of June and the driver training was carried out during the first week of July. Additional time was required on issues related to voluntary participation of the drivers, payment, privacy issues, handling collected data and driver rights. Figure 30 shows the proposed pilot test timeline.

Tractor #1 (yellow)
Tractor #2 (blue)

P&D: pickup and delivery (day shift)
LH: line-haul (evening shift)

	Weeks							
Driver	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16
#1-P&D	baseline	LPM						
#2-LH	baseline	LPM						
#3-P&D	baseline	LPM						
#4-LH	baseline	LPM						
#5-P&D			baseline	LPM				
#6-LH			baseline	LPM				
#7-P&D			baseline	LPM				
#8-LH			baseline	LPM				
#9-P&D					baseline	LPM		
#10-LH					baseline	LPM		
#11-P&D					baseline	LPM		
#12-LH					baseline	LPM		
#13-P&D							baseline	LPM
#14-LH							baseline	LPM
#15-P&D							baseline	LPM
#16-LH							baseline	LPM

Figure 30: Pilot test timeline

Subtask 6.2: Pilot Test

The pilot test was launched on July 7, 2014 and completed on November 7, 2014. The two research vehicles used in the Pilot Test were 2014 Freightliner Cascadia 4x2 (2 axle) conventional truck-tractors. These trucks were built to specification for, and purchased by Con-way Freight. The tractors were built with the Eaton Ultra shift automated transmission and subsequently equipped with the LPM technology and data acquisition systems by Eaton and UMTRI. A picture of one of the tractors is shown in Figure 31. Originally, sixteen commercial drivers from Con-way's Detroit terminal were recruited to volunteer to participate. Ultimately, only 13 of these drivers completed the study. All drivers were male, licensed commercial drivers with Group A qualifications. Drivers operated the specially-instrumented trucks, conducting Con-way's normal business, over approximately a 4-month period from June 30 thru November 7, 2014. Con-way Freight runs two types of routes, five days a week, out of the Detroit terminal: 1) pick-up and delivery (P&D) routes that run during the daytime with single trailers ranging from 28 to 53 feet in length and 2) line-haul (LH) routes that run predominantly during the nighttime and generally pulled a set of two 28-foot trailers. As such, two drivers used the same truck on a daily basis, one for P&D and one for line-haul. The nature of the P&D routes includes significant driving on surface streets, whereas line-haul routes are almost exclusively conducted on limited access roads. This combination of route types allowed for the evaluation of the LPM system in two distinctly different roadway environments.

The field operational test employed a within-subject experimental design where each driver operated a truck in both baseline and treatment conditions over a 4-week period. For the first two weeks of the Pilot Test, the trucks operated in the baseline condition without LPM functionalities provided to the drivers, but with all sensors and equipment running in the background. For the next two weeks (week 3 and 4) of driving, the LPM was enabled. Objective measures of the integrated system, vehicle, and driver performance were collected during the entire Pilot Test. The data set collected from the Pilot Test for the 13 drivers who participated represents 47,256 miles, 4,628 trips, and 1442 hours of driving.

Figure 31: Profile of a Con-way Test Tractor

Task 7.0 - Technology Evaluation

Table 14: Task 7 Activities

Task Name	Start	Finish
Task 7: Technology Evaluation	**Thu 1/16/14**	**Fri 11/28/14**
7.1 Test Validity and System Effectiveness Analysis	Mon 7/7/14	Fri 11/28/14
7.2 Independent Fuel Economy Impact Study	Tue 5/27/14	Fri 11/28/14
7.3 Cost Analysis and Technology Benefit	Thu 1/16/14	Fri 11/28/14

Subtask 7.1 and 7.2: Test Validity and System Effectiveness Analysis and Fuel Economy Impact Study

The technology evaluation was carried out following the completion of the pilot test by UMTRI and ORNL. These reports have been submitted to DoE [10]. A separate analysis was performed on the fuel saving potential of V2X technology [18]. This evaluation was based on data collected with the Eaton test vehicles on Michigan Test-bed located on telegraph road in Southfield, Mi. This analysis is presented at the end of this section.

The following section contains analysis presented by UMTRI and ORNL. The summary of the findings by UMTRI and ORNL are presented first followed by the detailed analysis reports.

Summary of UMTRI evaluation

The findings from the study, as reported here, fall into three distinct categories, namely:

- Objective results detailing the exposure of the driver’s to the LPM
- Objective results detailing the effect of LPM on fuel consumption
- Subjective results summarized from a questionnaire given to each driver after the study

Exposure and Sleep Button Use Findings

The findings related to exposure and the Sleep button was as follows:

1. Overall, 13 drivers travelled 47,256 miles during the study period of 130 days between June 30 and November 7, 2014.
2. A total of 4,628 trips were logged during the Pilot Test. The overall average distance per trip was 10.21 miles.
3. Of the total distance: 25,235 miles were traveled in baseline and 22,020 in treatment.

4. P&D drivers fall into two groups in terms of total distance travelled: drivers 1 to 4 travel between 700 and 1,000 miles during their exposure, whereas, drivers 5 to 8 logged between 1,500 and 2,700 miles. The increase exposure for drivers 5 to 8 are due to generally longer trips servicing regions of S.E. Michigan that are further from the distribution terminal.
5. Overall 35 percent of all treatment miles were traveled in LPM Control Mode, with LH drivers logging 37and P&D 30 percent.
6. All drivers used the Sleep button at least once during their treatment period.
7. Overall P&D drivers used the Sleep button 224 times to temporary disable the LPM, while LH drivers used it 181 times.
8. Eight drivers used the Sleep button at least once to permanently disable the LPM. Five drivers never used the Sleep button to permanently disable the LPM.

Fuel Consumption Findings

The findings related to fuel consumption were as follows:

1. The LPM system decreased fuel consumption for 5 out of 8 P&D drivers. The fuel saving was in the range of 2 percent to 13 percent when comparing similar driving conditions in the baseline and treatment (LPM Active only) exposure periods (i.e., no cruise control engaged, speed above 25 mph and no brake or turn-signal active time).
2. The LPM system decreased fuel consumption for all LH drivers. The fuel saving was in the range of 3 percent to 13 percent when comparing similar driving conditions in the baseline and treatment (LPM Active only) exposure periods (i.e., no cruise control engaged, speed above 25 mph and no brake or turn-signal active time).
3. The effectiveness of the LPM at reducing fuel consumption appears to be a function of vehicle speed. The greatest benefit coming from speeds above 55 mph.
4. The overall reduction in fuel consumption was 6 percent for all drivers and 7 percent for LH drivers when comparing similar driving conditions in the baseline and treatment (LPM Active only) exposure periods (i.e., no cruise control engaged, speed above 25 mph and no brake or turn-signal active time).
5. The overall reduction in fuel consumption was 2 percent for all drivers and 3 percent for LH drivers when considering the fleets’ total fuel used during the treatment period.

Subjective Questionnaire Findings

The findings related to the survey completed by each driver were as follows:

1. Overall, drivers appeared to agree that it was easy to understand how the LPM operated, was engaged, and how it was overridden. Drivers generally agreed that the LPM saved fuel on both freeways and city streets, although there appeared to be less certainty about city streets.

2. With respect to control authority and operations, drivers seemed confident that they were able to distinguish when they or the LPM had control authority. There were, however, concerns about the reasonableness of the speed limits imposed by the LPM, both in the ratings and in the drivers comments on the survey.
3. Finally, most drivers believed the display was easy to understand, however, there were some concerns about the accuracy with which the display reflected road conditions. It is likely that this concern was specifically related to discrepancies or delays in the LPM's identification of the current posted speed limit.

Summary of ORNL's Evaluation

A rigorous approach was applied to quantify the fuel savings benefit of the LPM system, based on the measured vehicle usage. The usage was characterized by developing synthetic drive cycles having very similar bivariate distributions of speed and acceleration as the measured test data. The synthetic cycles developed for the P&D LPM enabled and P&D LPM disabled cases were then used to estimate the difference in fuel consumption for the vehicle usage using Autonomie vehicle performance simulations. This calculation indicated a fuel savings of 1.74% with the LPM system for the P&D application. Limited resources for the project made completion of the same synthetic drive cycle analysis for the LH application not possible, however an analysis based on tractive energy considerations results in estimates for fuel savings of 1.33% with the LPM system for the LH application and 4.90% for the P&D application. The discrepancy between the two approaches is believed to be due to a low correlation between the mass specific fuel consumption per unit distance and the mass specific driving tractive energy per unit distance for the P&D usage. The correlation was considerably higher for the LH application, and it is believed that the overall fuel savings for the LH usage evaluated is within a range of 0.9-1.7%. However, additional research is needed to further evaluate the limitations of the two approaches in quantifying fuel savings.

Summary of Fuel Saving Potential of V2X Technologies

This evaluation explored the fuel economy and greenhouse gas emissions improvements possible in commercial vehicles by utilizing V2V/V2I information. Simulation results indicate the fuel saving potential of such technology in heavy duty trucks. These estimates, when extrapolated to all heavy-duty vehicles on U.S. highways, indicate that the cumulative fuel savings from all trucks in the U.S. could exceed one hundred million gallons annually from widespread deployment of SPaT V2I communications. In addition, the results indicate that the fuel economy improvement potential is a function of how far away the SPaT information is received from the signal intersection. This research highlights the benefits of long-range V2I and V2V data communications for improving fuel efficiency of vehicles. Future ITS developers should consider communications strategies that will provide optimum benefits for fuel economy and other environmental applications, which can have very different requirements than what is needed for more traditional safety applications.

UMTRI's Evaluation Report:

Objective Data Results

The results shown below were derived using numerical and video measures captured by the UMTRI DAS during the Pilot Test. The results shown below contain the following:

- Description of travel and exposure of the LPM to various driving conditions relevant to understanding the performance of the LPM and drivers' experience.
- Description of the LPM's actions during the field test, including the type and frequency of interventions through the driver displays and/or engine torque limitations
- Description of how the LPM changed the speed profile comparing baseline and treatment modes and summary fuel consumption findings based on fuel use as reported by the vehicle, via the J1939 CAN Bus, and recorded by the UMTRI Data Acquisition System (DAS).

Mileage and Trip Count Summary by Driver and Driver Category

A high level summary of the Pilot Test is shown in Table 15. The table shows summary dates, trip count and distance traveled by each driver, the two driver categories and for all study subjects. The left-most column contains the assigned driver identification number. The numbers 1 to 8 were assigned to Pick-up and Delivery (P&D) drivers; numbers 101 to 105 were used for Line-haul (LH) drivers. The third column from the left contains the tractor number assigned to each driver. Exposure dates are shown in the second group of columns from the left. All dates are for calendar year 2014. The Start date indicates when the drivers began their baseline driving (all data were collected in baseline but no LPM control was used). The Change date indicates when the system was switched from baseline to treatment. The End date column indicates when the driver was finished with the test and returned to their assigned non-study tractor. Trip counts are shown in the center of the table for both baseline (Off) and treatment (LPM) and both (All).[1] Similarly, the distance traveled by each driver in the baseline, treatment and all is shown in the second column from the right. Finally, the right-most column shows the fraction of distance with LPM as a function of the total distance.

Summary observations from Table 15 include:

[1] A trip is defined as the time between ignition on and ignition off. This time is assigned a unique id in the data architecture and along with a unique identification number for the tractor form the primary index into trip level summary tables in the database.

1. Overall, 13 drivers travelled 47,256 miles during the study period of 130 days between June 30 and November 7, 2014.
2. A total of 4628 trips were logged during the Pilot Test. The overall average distance per trip was 10.21 miles.
3. The Pilot Test lasted for 130 consecutive days with an overall average of 36 trips per day for both tractors (this average assumes travel 7 days per week. Using 6 travel days per week—consistent with Con-way operating schedule—the average is 42 trips per day for both tractors).
4. Of the total distance: 25,235 miles were travelled in baseline and 22,020 in treatment, thus 44 percent of the distance travelled was in the treatment condition. This percent is consistent for both P&D and LH at 44 and 45 percent, respectively.
5. For individual drivers, the percent of treatment distance ranges from 32 for driver 101 to 67 for driver 8.
6. P&D drivers fall into two groups in terms of total distance travelled: drivers 1 to 4 travel between 700 and 1,000 miles during their exposure, whereas, drivers 5 to 8 logged between 1,500 and 2,700 miles. The increase exposure for drivers 5 to 8 are due to generally longer trips servicing regions of S.E. Michigan that are further from the distribution terminal. Also, seasonal variation in Con-way's business accounts for part of the increase since September, October and November are traditionally a more busy time as manufactures increase their inventories to cover the holidays in late November and December.
7. For Line-haul drivers, the difference in total distance traveled is a reflection of their route. These drivers move freight between the same two or three distribution terminals on a daily basis. Drivers with longer routes logged more distance during their exposure period.
8. For both LH and P&D, differences between total baseline and treatment distance travelled is due to holiday-time-off, vacation-time-off, sick-time-off, and Con-way's driver seniority model. When there is a temporary vacancy in the delivery schedule, the option to change delivery routes and fill the opening is given to the more senior drivers first. Depending on the situation, this lead to the Pilot Test tractors being idle, since during a treatment time, only trained and consented drivers could use the study tractors with the LPM functionality.

Table 15: Mileage and Trip Count Summary by Driver and Driver Category

Individual Driver Exposure Summary												
			Exposure Dates			Trip Count			Distance, miles			LPM
Driver	**Type**	**Tractor**	**Start**	**Change**	**End**	**Off**	**LPM**	**All**	**Off**	**LPM**	**All**	**Fraction**
1	P&D	3235	30-Jun	18-Jul	30-Jul	324	186	510	618	367	985	0.37
2	P&D	3234	30-Jun	18-Jul	1-Aug	259	164	423	613	342	955	0.36
3	P&D	3235	4-Aug	18-Aug	26-Aug	186	88	274	484	205	689	0.30
4	P&D	3234	4-Aug	18-Aug	29-Aug	357	258	615	598	374	972	0.38
5	P&D	3235	2-Sep	19-Sep	3-Oct	380	247	627	1006	646	1652	0.39
6	P&D	3234	2-Sep	19-Sep	3-Oct	218	119	337	1191	1118	2309	0.48
7	P&D	3235	5-Oct	27-Oct	3-Nov	209	146	355	706	849	1555	0.55
8	P&D	3234	6-Oct	27-Oct	7-Nov	209	239	448	900	1844	2744	0.67
101	LH	3235	30-Jun	19-Jul	30-Jul	146	75	221	3268	1560	4828	0.32
102	LH	3234	30-Jun	19-Jul	2-Aug	180	112	292	5419	3173	8592	0.37
103	LH	3235	4-Aug	14-Aug	30-Aug	66	81	147	3053	3627	6681	0.54
104	LH	3234	4-Aug	16-Aug	30-Aug	100	89	189	3796	3865	7662	0.50
105	LH	3234	2-Sep	13-Sep	4-Oct	99	91	190	3582	4050	7632	0.53
Driver Category and Overall Exposure Summary												
P&D		All	30-Jun		7-Nov	2142	1447	3589	6116	5745	11861	0.44
LH		All	30-Jun		4-Oct	591	448	1039	19119	16275	35395	0.45
All	All	All	30-Jun		7-Nov	2733	1895	4628	25235	22020	47256	0.44

LH = Line-haul

P&D = Pick-up and Delivery

LPM = Treatment (LPM On)

Off = Baseline (LPM Off)

Exposure Summary for LPM Treatment Period for each Driver and Driver Category

Table 16 shows the exposure summary results for the treatment period for each driver and driver category. There were four general states that the LPM could be in during the treatment period. These states and the distance traveled in each state is shown on the left-side of the table along with a column that shows the aggregated total distance traveled during the treatment period. A brief definition of each state (from left to right in the table) is provided below. Please refer to [16] for a more detailed definition.

- LPM Inactive—similar to baseline, the LPM does not actively control the vehicle speed or commanded throttle. Additionally, in this state the interface to the driver via the DVI monitor is blank and flat black with only the words "LPM Inactive" shown.
  - Driver Mode—similar to baseline, the LPM does not actively limit vehicle speed or commanded throttle. This mode is needed to let the driver know that they are in control and the LPM system will not restrict/or reduce the throttle commands made by the driver via the accelerator pedal.
  - LPM Control Mode—this is the state that actively commands engine torque to either limit vehicle speed or reduce transients. When in Control mode the LPM DVI shows what it has determined to be the current posted speed limit or the maximum fleet limit when on the freeway or if the posted speed limit is unknown.
  - LPM Transition Mode—is a temporary mode used to indicate to the driver that the LPM system is changing between Driver and Control modes.

In addition to the travel distances for each of these states, the right-most columns of Table 16 show the fraction of treatment miles in each of these states. Summary observations from this table are:

1. Of all treatment distance travelled by all drivers, over half (54 percent) was in the LPM Inactive state (see the next section and table for a more complete breakdown of LPM Inactive).
   a. The fraction of LPM Inactive ranged between 0.07 for driver 5 to 0.82 for driver 105.
   b. The average fraction of LPM Inactive was 0.46 and 0.56 for P&D and LH drivers, respectively.
   c. A significant fraction of LPM Inactive distance occur in both driver categories, however, none of the LH drivers had less than 38 percent of their driving distance in LPM Inactive compared to two P&D driver with less than 10 percent of their driving distance in LPM Inactive.
2. There was a big difference in the amount of travel in LPM Driver Mode as a function of driver category. The fraction of distance travelled in LPM Driver Mode was 0.23 for

P&D and only 0.04 for LH. This is due to the different duty cycles between these driver categories. P&D is urban delivery dominated by travel on surface streets with frequent stops and turns as compared to LH which is predominately high-speed, limited-access freeway driving. The fraction of distance for LPM driver mode ranged from 0.03 to 0.07 for LH and 0.11 to 0.37 for P&D.

3. Overall 35 percent of all treatment miles were traveled in LPM Control Mode, with LH drivers logging 37 and P&D 30 percent. Driver 5, a P&D driver, had the largest fraction of LPM Control mode distance at 0.64. Driver 8 and driver 105 had the smallest fraction at 0.13 and 0.14, respectively. In terms of gross exposure to LPM Control, driver 3 had the fewest overall miles with 101 miles travelled in this state while driver 102 had the most overall miles with LPM Control active at 1778 miles.
4. Transition mode accounts for about 2 percent of all treatment miles. The only noteworthy exception is driver 103 with the fraction of transition to treatment miles at 5 percent. Driver 103 traveled 173 miles in transition mode, more than three times more than any other driver. In general, P&D drivers had fewer miles in Transition mode compared to LH drivers. This may be due to the increased frequency of throttle modulation for P&D drivers as they negotiate a surface-street urban driving environment, compared to LH drivers who predominantly drive at constant speeds on freeways, thus not needing to modulate the accelerator pedal.

Table 16: Exposure Summary for LPM Treatment Period for each Driver and Driver Category

Individual Driver Exposure Summary for LPM Treatment Period									
	LPM Mode: Distance, miles					**LPM Mode: Fraction**			
Driver	**LPM Inactive**	**Driver Mode**	**LPM Active**	**Trans Mode**	**All States**	**LPM Inactive**	**Driver Mode**	**LPM Active**	**Trans Mode**
1	192	58	114	3	367	0.52	0.16	0.31	0.01
2	31	128	172	12	342	0.09	0.37	0.50	0.03
3	45	55	101	4	205	0.22	0.27	0.49	0.02
4	54	160	154	7	374	0.14	0.43	0.41	0.02
5	47	174	411	13	646	0.07	0.27	0.64	0.02
6	755	117	230	11	1114	0.68	0.11	0.21	0.01
7	436	128	280	4	848	0.51	0.15	0.33	0.00
8	1092	495	244	10	1840	0.59	0.27	0.13	0.01
101	663	45	805	48	1560	0.42	0.03	0.52	0.03
102	1196	137	1778	51	3162	0.38	0.04	0.56	0.02
103	1800	135	1509	173	3616	0.50	0.04	0.42	0.05
104	2175	251	1383	43	3852	0.56	0.07	0.36	0.01
105	3313	151	551	13	4027	0.82	0.04	0.14	0.00
Driver Category and Overall Exposure Summary for LPM Treatment Period									
P&D	2652	1315	1705	64	5735	0.46	0.23	0.30	0.01
LH	9146	718	6027	327	16217	0.56	0.04	0.37	0.02
All	11798	2032	7731	391	21953	0.54	0.09	0.35	0.02

P&D = Pick-up and Delivery (Driver 1 to 8)

LH = Line-haul (Driver 101 to 105)

Exposure Summary for LPM Inactive by Driver and Driver Category

To further investigate the overall performance of driver's use of the LPM system, consider Table 17. On the left-side of the table, the column LPM Inactive shows the total distance travelled by each driver in this state. The three columns to the right of LPM Inactive, show the distance travelled due to the main reasons for this state, namely: cruise control engaged, driver disabled and LPM fault. The final column, labeled "Other", is used to resolve any remaining LPM Inactive distance travelled not covered by the other three columns. The right-most four columns in the table show the corresponding fraction of distance travelled in each of these categories as compared to all LPM Inactive distance for each driver and driver group. Summary observations from this table are:

1. In terms of cruise control usage, there is a broad range of use among the 13 subject drivers.
    a. Five of the P&D drivers, 1 to 5, had no or very little cruise control engaged distance. This is not surprising; these drivers all had the fewest miles per trip on average, ranging from 1.5 to 2.6 miles per ignition cycle. The assumption being that cruise usage is less likely on short trips which mainly are on surface roads requiring frequent stops, turns, and transitions in speed thus making engaging the cruise control less beneficial in reducing the driver work-load. The other three P&D drivers, 6 to 8, had appreciable distance travelled with cruise control engaged. These drivers averaged between 4.4 and 6.8 miles per trip. In fact, approximately 61 percent of all LPM Inactive distance travelled by drivers 6 and 7 was due to having the cruise control engaged. In the P&D category Driver 8 had the most LPM Inactive distance but only 17 percent was due to cruise usage.
    b. Overall for P&D driver, 35 percent of the LPM Inactive miles were due to having the cruise control engaged.
    c. Four of the five LH drivers had appreciable cruise control engaged distance ranging from 58 to 99 percent. Driver 103 had the lowest relative amount at 11 percent. As a group, 68 percent of LH LPM Inactive distance was a result of cruise control engaged driving.
    d. Finally, for both P&D and LH drivers, engaging the cruise control was the single most reason for LPM Inactive distance during the treatment period of the Pilot Test. These results suggests that broadening LPM control to include cruise control engaged driving, will measurably increase the amount of distance that the LPM control algorithm can influence the rate of fuel consumption.

2. The Driver Disabled column in Table 17 shows the amount of LPM Inactive distance attributable to drivers permanently disabling LPM using the Sleep button on the DVI.[2] The effect of this action by the driver, varies considerable across all drivers and driver category. Driver 103 had the most distance traveled with the LPM system purposely Inactive. Approximately, 88 percent of Driver 103's LPM Inactive distance was due to selectively turning the LPM off. Conversely, six of the thirteen drivers never used the Sleep button to disable the LPM. For both driver categories, roughly half of the drivers used the Sleep button to disable the system at least once during their two week treatment period. This suggests that giving the driver this option maybe an important factor in driver acceptance, however, a two week exposure period to LPM is insufficient to measure the long term usage of this system control function.
3. The LPM Fault column shows the distance traveled during the treatment period when the LPM or DAS system showed a fault. To ensure the system and DVI worked correctly during the treatment period, both systems monitored a 'heart-beat' from the other and since the DIV monitor was being controlled by the DAS a separate heart-beat was monitored for that subsystem as well. For LH drivers, about 7 percent of the LPM Inactive distance was attributable to a fault. However, the average percentage was higher for P&D drivers at 43 percent. The primary reason for LPM Inactive distance due to a fault resulted from the LPM computer operating system presenting a dialog box requesting user input and hence not shutting down correctly on an ignition off event. This caused the LPM power controller to perform a hard shutdown which then causes the subsequent boot sequence to not complete and the cycle continues.
4. The column labeled "Other" in the table shows the LPM Inactive distance not accounted for by cruise, Sleep button, and faults. A review of these data show the following:
    a. These events only occurred on tractor 3234 which suggests perhaps a hardware intermittent problem on this tractor.
    b. Most of the distance attributable to any given driver in this category was accumulated in a single trip and hence this was a pretty rare event occurring approximately 4 times over 1895 trips or in about 0.05 percent of trips.
    c. Another possible explanation for these events is the driver used the Sleep button to disable the LPM before the DAS computer was fully operational and hence the button activity was not captured in the numerical data logged by the DAS.

[2] The Sleep button also allows drivers to temporarily disable the LPM. In these cases, however, the system switches to Driver control mode for a short period of time and is not disabled for the remainder of the trip. Whereas, a prolong depression of the Sleep button causes the LPM to switch to Inactive and remain in that state until the next power cycle.

Table 17: Exposure Summary for LPM Inactive by driver and driver category

Individual Driver Exposure Summary for LPM Inactive									
	Distance, miles					Fraction			
Driver	LPM Inactive	Cruise Engaged	Driver Disabled	LPM Fault	Other*	Cruise Engaged	Driver Disabled	LPM Fault	Other
1	192	11	9	171	0	0.06	0.05	0.89	0.00
2	31	0	0	31	0	0.00	0.00	1.00	0.00
3	45	0	24	22	0	0.00	0.52	0.48	0.00
4	54	0	0	54	0	0.00	0.00	1.00	0.00
5	47	3	12	32	0	0.06	0.26	0.69	0.00
6	755	458	0	66	231	0.61	0.00	0.09	0.31
7	436	265	127	44	0	0.61	0.29	0.10	0.00
8	1092	181	41	720	149	0.17	0.04	0.66	0.14
101	663	386	0	276	0	0.58	0.00	0.42	0.00
102	1196	1028	0	17	151	0.86	0.00	0.01	0.13
103	1800	196	1581	22	0	0.11	0.88	0.01	0.00
104	2175	1312	475	333	55	0.60	0.22	0.15	0.03
105	3313	3293	0	19	0	0.99	0.00	0.01	0.00
Driver Category and Overall Exposure Summary for LPM Inactive									
P&D	2652	918	213	1141	381	0.35	0.08	0.43	0.14
LH	9146	6215	2057	667	207	0.68	0.22	0.07	0.02
All	11798	7133	2269	1808	588	0.60	0.19	0.15	0.05

P&D = Pick-up and Delivery (Driver 1 to 8)

LH = Line-haul (Driver 101 to 105)

*The bulk of this distance for each driver is attributable to a single trip. For these data there was an LPM heartbeat (No LPM Fault), the cruise was not engaged, the LPM was not disabled by the driver, but the LPM mode was set to inactive.

Summary of GPS, Map and Radar System Faults

To further explore the total treatment distance traveled without the LPM in an active mode consider Table 18. This table shows a summary of the distance traveled with a GPS and or radar fault during the treatment period. When a fault occurred with the GPS or radar, the LPM went into Driver mode.

Map is included in the GPS column, since a failure to properly map the current GPS location within the Map software had the same effect on the system as a GPS receiver failure. Since the LPM uses a commercial grade GPS receiver, failure of this system was uncommon and only one event for driver 8 on tractor 3234 was an actual hardware failure (loose connection) required a visit to the fleet to investigate and identify the failure.

The vast majority of distance logged with a GPS/Map fault derives from the mapping errors with the current GPS location. These errors could be a result of inconsistencies within the mapping database but are more likely due to poor quality of the GPS location measures that result when the GPS receiver cannot ‘see’ more than two satellites or when the GPS receiver has lost the location information of the satellite constellation (ephemeral) and needs time to rebuild this information (this is the reason, it can take ten to fifteen minutes to establish a high quality fix with a GPS receiver in some instances).

In terms of the distance traveled in Driver mode as a result of faults in these subsystems, only Driver 8 had substantial accumulation at 79 percent (this is 21 percent of all treatment miles travelled by Driver 8). Other drivers with fractionally high amounts of travel distance due to these problems are Driver 103 and 105 at 0.34 and 0.31, respectively. However, as fraction of total distance traveled in treatment these distances only represent about one percent of all treatment miles. For most drivers and in most cases, distance accumulated in Driver mode resulted from travel below the minimum LPM speed threshold along with any distance traveled while braking, with the turn-signal on or while on ramps to and from limited access roadways or after the Sleep button was pressed, as discussed in the next section.

Table 18: Summary of GPS, Map and Radar System Faults

Summary for GPS, Map and Radar System Faults					
Distance, miles				Fraction	
Driver	**Driver Mode**	**GPS or Map**	**Radar**	**GPS/Map**	**Radar**
1	58	5.2	2.7	0.09	0.05
2	128	4.7	1.7	0.04	0.01
3	55	9.4	0.0	0.17	0.00
4	160	9.9	10.7	0.06	0.07
5	174	18.8	9.2	0.11	0.05
6	117	7.2	1.4	0.06	0.01
7	128	23.1	11.5	0.18	0.09
8	495	390.3	1.4	0.79	0.00
101	45	12.2	2.9	0.27	0.07
102	137	16.1	0.0	0.12	0.00
103	135	46.2	0.4	0.34	0.00
104	251	31.7	0.0	0.13	0.00
105	151	46.4	0.0	0.31	0.00
Overall Summary for GPS, Map and Radar System Faults					
P&D	1315	468	39	0.36	0.03
LH	718	153	3	0.21	0.00
All	2032	621	42	0.31	0.02

P&D = Pick-up and Delivery (Driver 1 to 8)   LH = Line-haul (Driver 101 to 105)

Sleep Button Use Statistics for Individual Drivers and Driver Categories

As implemented the LPM system was a passive technology in that it did not require input from the driver. There were no settings and the principal interface with the driver was through the DVI monitor which displayed which state the LPM was in, the current posted speed (or maximum fleet policy speed when posted was not available), sensor faults, and general information about road grade and traffic congestion as a mechanism for the driver to know why the tractor powertrain may not respond with the same fidelity under some conditions. The only real control the driver had over the system was with the ‘Sleep’ button. The Sleep button was bi-functional. A brief press of the Sleep button put the LPM into Driver mode for a 20 second period. A more sustained press of the Sleep button (5 seconds or longer) caused the LPM to become Inactive for the remainder of the trip.

The use of the sleep button for individual drivers and each driver category is shown below in Table **19**. The left-most four columns of the table show the number of temporary and permanent

Sleep button events for each driver. Also shown is the number of trips in which these events occurred and the maximum number of button events (both temporary and permanent) in any give trip for each driver. The center columns of the table show the distance traveled in LPM Active mode and a normalized average distance between each temporary button press. The right-most three columns of the table show the maximum, minimum and average time between consecutive temporary button presses across all trips with two or more events. Summary observations from this table are:

1. All drivers used the Sleep button at least once during the treatment period.
2. Overall P&D drivers used the Sleep button 224 times to temporary disable the LPM, while LH drivers used it 181 times. When averaged, temporary disable, was used 28 times per driver by P&D, LH was used 36 times per driver.
3. Eight drivers used the Sleep button at least once to permanently disable the LPM. Five drivers never used the Sleep button to permanently disable the LPM.
4. Driver 8 did not have the overall highest count of button presses (Driver 8 was the second highest), but did have the most in a single trip at 43.Driver 103 had the most button presses, both Temporary and Permanent at 135 and 16, respectively.
5. When the total Temporary count of button presses is normalized by the distance travelled in LPM Active, six of the eight P&D drivers had a button press event every 12 miles or less on average, with Driver 8 having on every 2.9 miles on average. Line-haul Driver 103, had a button press every 11.2 miles on average. Overall, for both driver categories, the Sleep button on average was used every 63 miles.
6. In terms of frequency of button use in a single trip, nine drivers repeatedly depressed the Sleep button within a 1 second period. This suggests the following:
    a. The system may not have responded quickly enough to a button press in terms of changing the DVI monitor to indicate the button was pressed.
    b. Many of the button presses could be the result of the driver intentionally depressing the button quickly and therefore the counts in the table may over-represent the use of this functionality. More representative count totals may be found if button presses were merged when within a time window.
    c. Multiple quick button presses also suggests that drivers may not have understood the function of the Sleep button. In one investigation, video showed a driver using the sleep button multiple times while passing a slower vehicle on the highway. This suggests that the driver may have thought that being in LPM Driver mode would result in higher speed, despite the fact that regardless of LPM mode or activation, the vehicle transmission was limited to the fleet policy speed of 62 mph.

Table 19: Sleep Button Use Statistics for Individual Drivers and Driver Categories

	Count				Distance, miles		Frequency		
	Sleep Button Events			Maximum	LPM	Average*	Avg. Time between Events, s		
Driver	Temp	Prmnt	Trips	Per Trip	Active	Per Event	Max	Min	Avg
1	17	2	12	5	114	6.7	624.5	6.8	327.3
2	18	0	10	7	172	9.5	1115.9	8.4	449.8
3	33	4	10	9	101	3.1	202.1	0.3	20.9
4	2	0	1	2	154	76.8	34.3	34.3	34.3
5	6	2	3	4	411	68.5	23.0	0.9	15.6
6	38	0	11	19	230	6.1	821.4	0.3	129.9
7	25	6	14	3	280	11.2	488.7	0.3	119.8
8	85	4	14	43	244	2.9	4099.8	0.3	393.2
101	6	0	3	3	805	134.2	27.4	0.3	13.9
102	7	0	5	2	1778	254.0	56.3	52.8	54.6
103	135	16	22	28	1509	11.2	4470.3	0.3	407.4
104	23	10	12	4	1383	60.1	3134.0	0.3	759.9
105	10	0	3	6	551	55.1	8.6	0.3	1.4
Driver Category and Overall Sleep Button Use Statistics									
P&D	224	18	75	43	1705	23	926.2	6.5	186.3
LH	181	26	45	28	6027	103	1539.3	10.8	247.4
All	405	44	120	43	7731	63	1232.8	8.6	216.9

P&D = Pick-up and Delivery (Driver 1 to 8)
LH = Line-haul (Driver 101 to 105)
Temp = Temporary Sleep Button Effect on LPM
Prmnt = Permanent Disable of the LPM
*Average is based on the count of temporary sleep button events

Speed Distributions Comparing Baseline and Treatment

The effect of LPM on speed is illustrated in Figure 32 for P&D drivers and Figure 33 for LH drivers. Each of these figures shows speed along the x-axis and data point count along the y-axis. The number of data points that constitute the distributions for both baseline and treatment is the same. The treatment time is only for LPM Active mode. To make the number of baseline points equal to treatment points (i.e., the same amount of time), the baseline points were sub-sampled across all driving time for all the drivers in each category for speeds above 25 mph with no brake or turn-signal active. The sub-sampling was done using a gain function on the rank of all data points in the baseline period and was derived by taking the total number of baseline points divided by the total number of treatment points. This gain was then crossed with each data point rank and truncated to an integer. Integer values were then grouped and the minimum time associated with each value was used to uniformly sub-sample the data across all driving time. This procedure ensures that the data represented in each distribution has following qualities:

1. It represents the same total amount of time for each condition exactly.
2. It maximizes the total amount of time in the treatment condition (LPM active).
3. It distributes in a normalized fashion the companion data (baseline) across all drivers and trips.
4. It assumes that collectively, a sub-sample of a distribution is inherently the same as the original distribution, given that sample size of both distributions is very large. For P&D and LH drivers the sample size is 1.3 and 1.8 million points, respectively.

For the P&D drivers, the distributions show stark differences. In treatment (LPM active mode only) the LPM prevents the vehicle from exceeding what the system has determined is the posted speed limit. This is clearly shown in the figure by the higher counts at 35, 40, 45, and 55 mph relative to the baseline data which shows a more uniform distribution across these speed thresholds. For the speed ranges between 41 and 44 and between 46 and 49 mph, there are more counts in the baseline state; this suggests that in the baseline mode drivers spent more time at these intermediate speeds than they did in treatment.

Approximately the same amount time was spent in the lower speed range, between 25 and 35 mph, for baseline driving compared to treatment.

The figure also shows a difference around the maximum fleet policy speed of 62 mph. The peak speed is 62 mph for both baseline and treatment, but there is far more data at this speed in baseline. Also, in baseline the distribution bin at the next higher speed (62.5 mph) has significantly higher count than the corresponding bin in treatment. However, for speeds between

60 and 62 mph, the treatment bins have higher counts than baseline. This suggests that in baseline drivers were able to spend more time at a maximum speed that was greater than the maximum speed in treatment. In other words, the LPM restricted the maximum speed of the truck to between 60 and 62 mph more often than in baseline were drivers spent most of their time between 61.5 and 62.5 mph. The premise that overall baseline speeds were greater than treatment speeds is also reflected in the summary statistics for the figure, where the average speed was 43.6 and 43.1 mph for baseline and treatment, respectively. Similarly, the median speed was 41.1 and 40.5 mph for baseline and treatment, respectively.

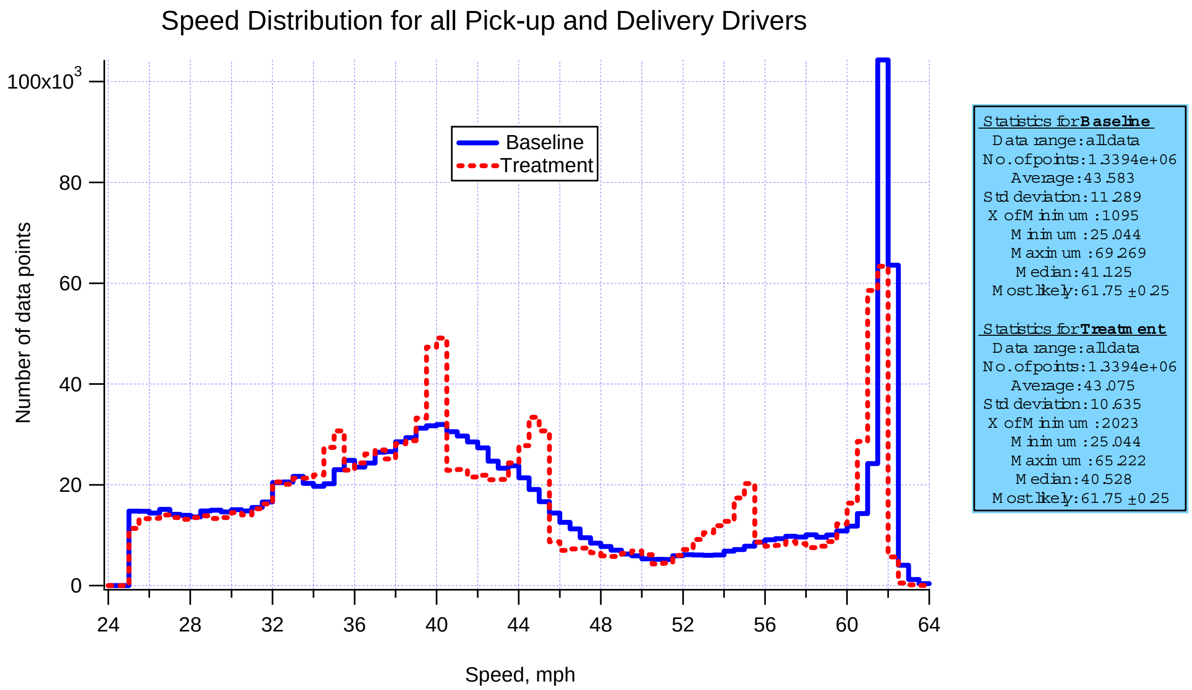


Figure 32: Baseline and Treatment Speed Distribution for all P&D Drivers

Figure 33 shows baseline and treatment (LPM Active only) distribution of speed for Line-haul drivers. This driver group predominantly travels on limited access roads which is reflected in the figure by large amounts of time at speeds above 60 mph. Similar to the P&D baseline and treatment speed distributions shown in the previous figure, there are two lower speed values, one at 55 and another less pronounced at 45 mph, in treatment mode that reflect the speed restriction of the LPM when the posted-speed is available from the mapping software. Also similar to the P&D distributions but even more pronounced for LH is the narrow speed range of baseline driving between 61 and 62.5 mph as compared to a much broader treatment speed distribution between 58 and 62 mph. These summary statistics suggest a similar overall speed finding, when compared to the P&D. For LH the average speed in baseline is greater than treatment with 59.1 and 58.0 mph for baseline and treatment, respectively. Similarly, the median speed was 61.7 and 60.5 mph for baseline and treatment.

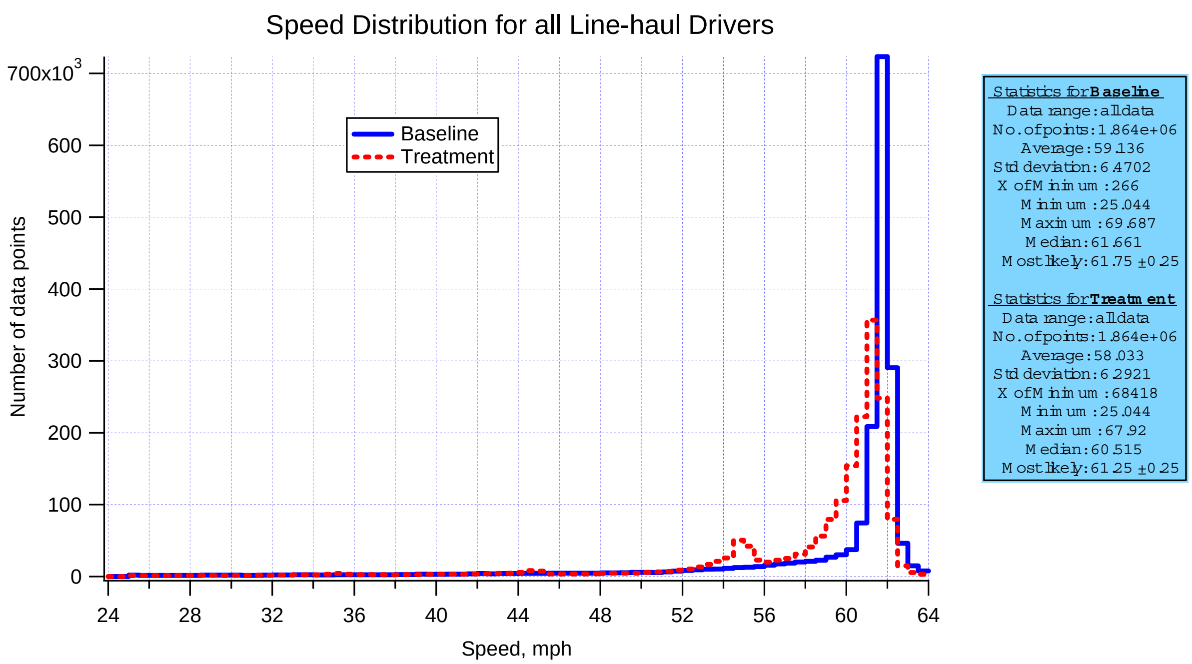


Figure 33: Baseline and Treatment Speed Distribution for all Line-haul Drivers

In summary, these figures show the following:

- The shape of the speed distribution for treatment differs significantly from baseline due to the posted speed limit constraints the LPM imposes on vehicle maximum speed for a given road. This is particularly pronounced for P&D drivers but can also be seen in the LH distributions too.

- For both LH and P&D speed distributions, the speed distribution near the fleet policy speed of 62 mph is both slower and more dispersed in treatment compared to baseline condition
- For these data, which are uniformly sampled across all drivers and system state, the P&D drivers went on average 0.5 mph faster in baseline than treatment, while the LH drivers went on average about 1.1 mph faster in baseline than treatment.

Fuel Rate Distributions Comparing Baseline and Treatment Conditions

Figure 34 and Figure 35 show baseline and treatment distributions of Fuel Rate for P&D and LH drivers, respectively. Fuel rate is shown along the x-axis of each figure and is grouped using a bin width of 2 liter/hour. The y-axis shows the number of data points in each bin. In both figures, the amount of time represented in baseline and treatment is the same, so a normalized distribution would have the exact same shape. As mentioned above with the speed histograms, but explained in more detail here, the data reported in this section have the following characteristics:

- Fuel rate values were only sampled at speeds above 25 mph, which is the minimum threshold speed for LPM and only with the brake and turn-signal off
- All driving in both states is manual speed control with cruise control off.
- Fuel rate values reflect the consumption measured by the engine and reported on the J1939 CAN bus. The absolute accuracy of this measurement is known to be problematic, however, this analysis is a comparative study done by looking at the relative accumulation of fuel use in two different states. This measurement inaccuracy is similar to other confounding influences like load, route, weather conditions, tire-inflation pressure, etc. Since the test design was serial with sets P&D and LH drivers using the vehicles on the same schedule and for a relative short period of time (2 weeks in each condition) before the next set of drivers, the influence of these effects are assumed to be randomly scattered throughout the data collection period and hence equally influential in both the baseline and treatment conditions. That is to say, there is no known influence, other than the state of the LPM and how the driver reacts to the system that can explicitly explain the fuel consumption differences between these two states. Mass is considered in the analysis performed by ORNL, as presented in the next section.
- All fuel consumption results are balanced with respect to the time and sampling. The results shown in Figure 34 thru Figure 39 always represent the same amount (identical count) time for baseline and treatment (LPM Active) condition. For every sub-sample set of data the count in the baseline and treatment conditions are compared and the set with more data is then sub-sampled in an evenly distributed fashion across all drivers, trips and time to ensure that the data from the two conditions have no inherent bias. That is, all

drivers, load conditions, weather effects, number of trips, time within a trip, etc. are fully represented by an equal amount of data in both baseline and treatment conditions.

For Figure 34 and the fuel rate of P&D drivers, consider the following observations:

1. In baseline, P&D drivers used 741 liters of fuel as compared to 715 liters in treatment (LPM Active). These totals reflect the total fuel used over a sample size that represents 37.2 hours of driving in each state.[3] This reflects a 4 percent decrease in fuel use with the LPM engaged.
2. A difference in the distributions is at or near the 0 liter/hour fuel rate for baseline and treatment. In baseline, there was more time (9 percent) in this very low fuel rate state as compared to treatment.
3. Another area of difference is between 10 and 14 liter/hour. In this case, the treatment distribution has higher counts compared to baseline. Similarly, but not as pronounced are the higher counts for treatment between 30 and 40 liter/hour range.
4. In terms of statistics, the average was 19.9 and 19.2 liter/hour for baseline and treatment, respectively. The median was 17 and 16.2 liter/hour for baseline and treatment, respectively.

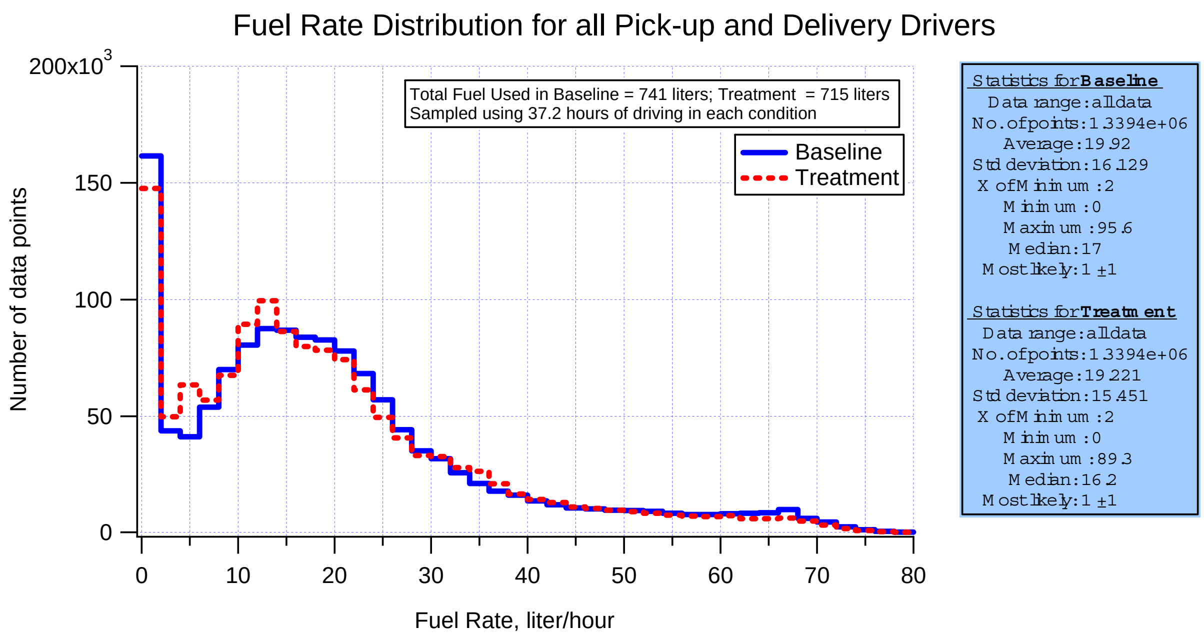


Figure 34: Baseline and Treatment Fuel Rate Distribution for all P&D Drivers

[3] The samples size used was 1339392 data points (the data collection rate was 10 Hz). This sample size was used simply because it allowed easy transfer of data with the computer clipboard to a plotting program for illustration and binning.

For Figure 35 and the fuel rate distributions of LH drivers, consider the following observations:

1. In baseline, LH drivers used 1427 liters of fuel as compared to 1340 liters in treatment (LPM Active). These totals reflect the total fuel used over a sample size that represents 51.7 hours of driving in each state. This reflects a 7 percent decrease in fuel consumption with the LPM engaged.
2. A large difference in the distributions is at or near the 0 liter/hour fuel rate for baseline and treatment. In baseline, there was significantly more time (36 percent) in this very low fuel rate state as compared to treatment.
3. In general, the fuel rate for treatment is greater than baseline between 4 and 44 liter/hour, while from 45 to 70 liter/hour baseline is greater than treatment. This is particularly true for rates between 55 and 67 liter/hour.
4. In terms of statistics, the average was 27.6 and 25.9 liter/hour for baseline and treatment. The median was 26.2 and 25.8 liter/hour for baseline and treatment.

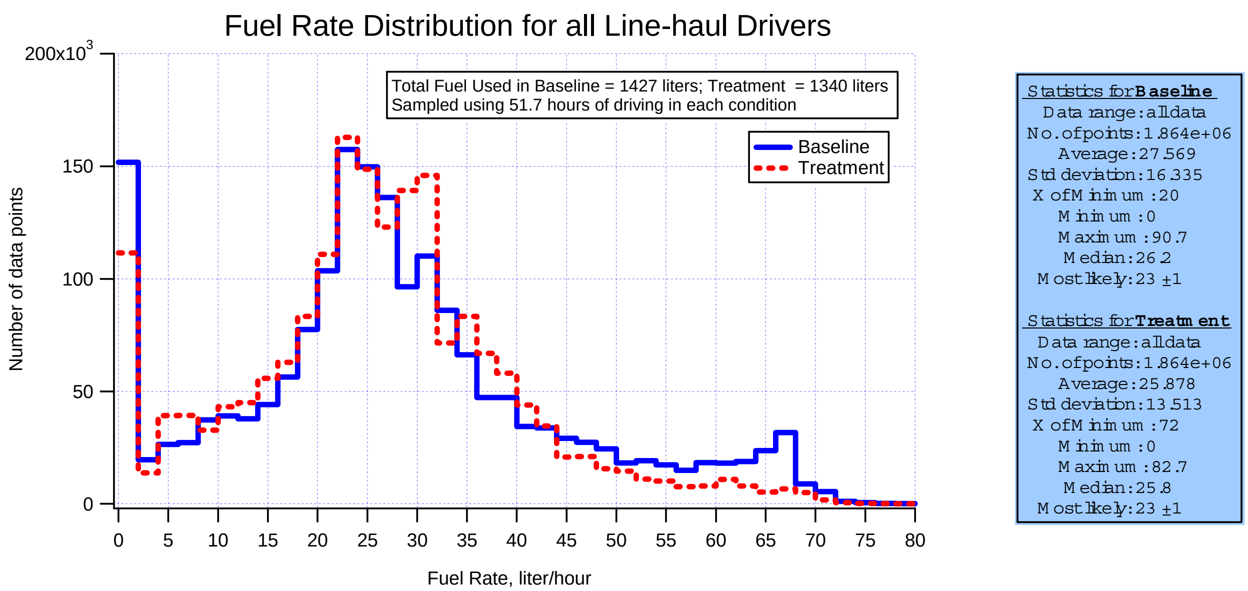


Figure 35: Baseline and Treatment Fuel Rate Distribution for all Line-haul Drivers

Total Fuel Used as a function of Speed Range, Driver and Driver Category

Figure 36 through Figure 39 show total fuel used by each driver in four different speed categories. The fuel used is derived by aggregating all fuel rate values measured by the engine and reported on the J1939 CAN bus. All fuel use values shown in these figures are balanced with respect to the time and sampling. The results shown in Figure 36 through Figure 39 always represent the same amount (identical count) of time for baseline and treatment (LPM Active) condition. For every sub-sample set of data the count in the baseline and treatment conditions are compared and the set with more data is then sub-sampled in an evenly distributed fashion across the trips for each driver to ensure that the data from the two conditions have no inherent bias. The additional constraint of a speed threshold is also used in the total fuel used derivation. Observations related to these figures follow:

- For the speed range between 25 to 35 mph, as shown in Figure 36, six of the thirteen drivers used more fuel in treatment compared to baseline.
- For the speed range between 35 to 45 mph, as shown in Figure 37, three of the thirteen drivers used more fuel in treatment compared to baseline.
- For the speed range between 45 and 55 mph, as shown in Figure 38, four of the thirteen drivers used more fuel in treatment compared to baseline.
- For the speed range between 55 and 65 mph, as shown in Figure 39, P&D drivers 2 and 4 had no comparable time in this speed range. Of the remaining eleven, two used more fuel in treatment compared to baseline. However, for the LH drivers, all used less fuel in baseline compared to treatment.

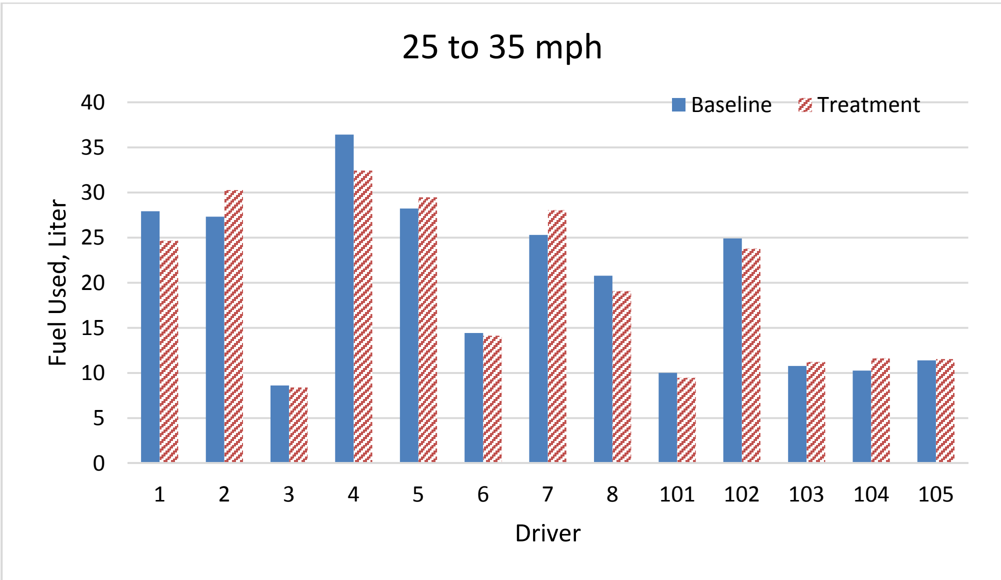


Figure 36: Total Fuel Used for each Driver in the 25 to 35 mph Speed Range

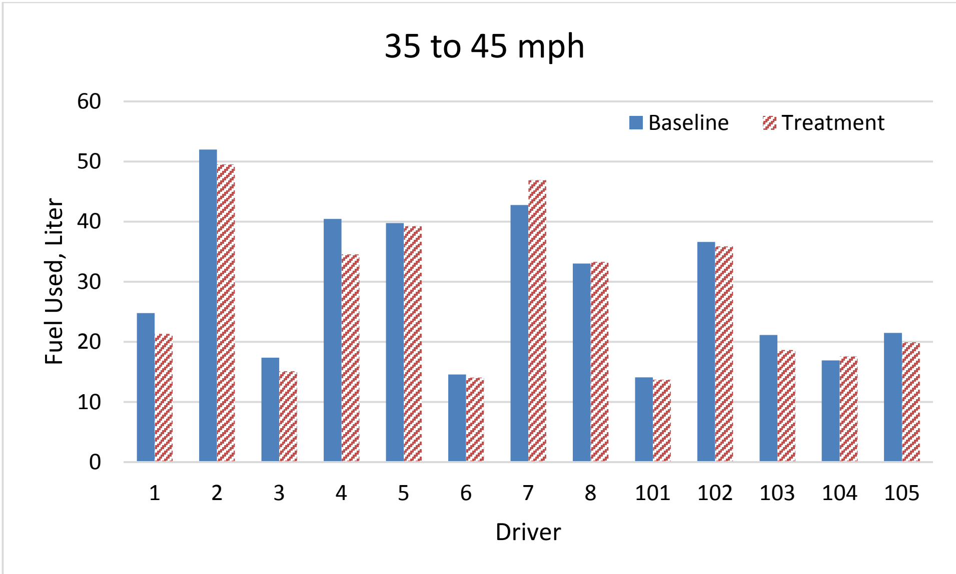


Figure 37: Total Fuel Used for each Driver in the 35 to 45 mph Speed Range

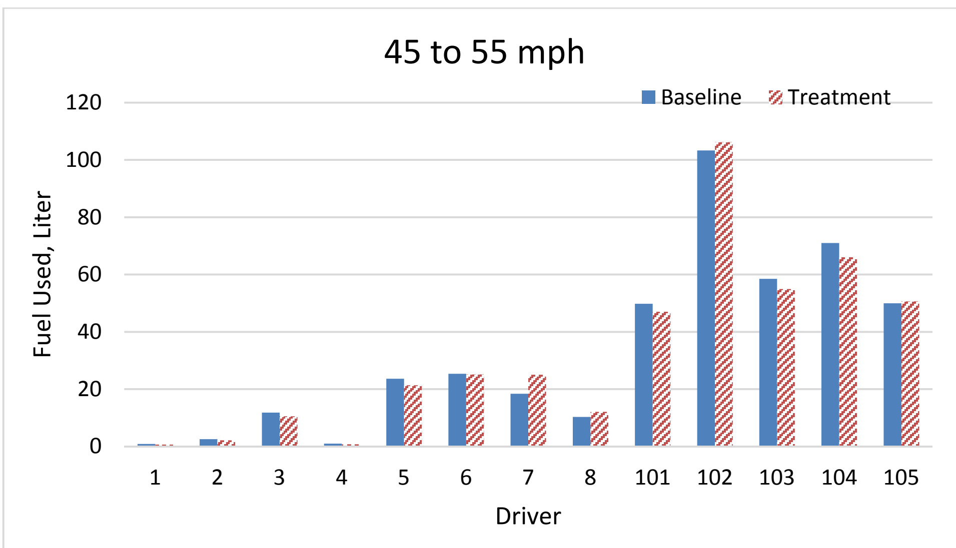


Figure 38: Total Fuel Used for each Driver in the 45 to 55 mph Speed Range

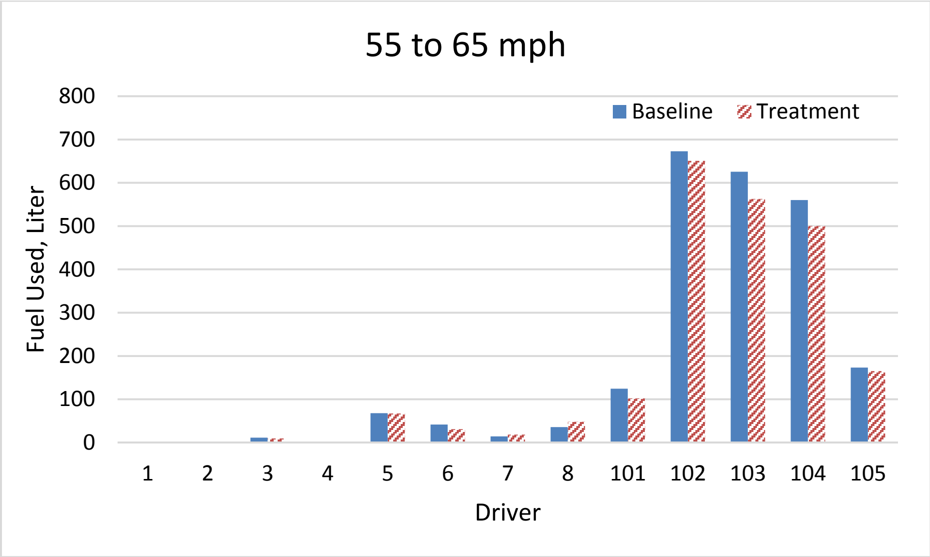


Figure 39: Total Fuel Used for each Driver in the 55 to 65 mph Speed Range

A summary of the fuel used by P&D, LH and all drivers as function of speed is shown in Table 20. The table shows Speed Range and Driver categories on the left, total fuel used for baseline and treatment (LPM Active only) and the total amount of time (hours) in *each* state used in the comparison. The right-most column shows the fraction of treatment to baseline fuel used. A fraction value greater than 1.0 indicates that more fuel was consumed in baseline compared to treatment. General observations from these data include:

- For P&D drivers, speed range does not seem to influence the overall amount of fuel consumed between baseline and treatment. LH drivers do seem to trend toward using less fuel in treatment compared to baseline with increasing speed.
- For both driver categories, the 35 to 45 mph category shows more fuel savings in treatment, than the 45 to 55 mph speed range.
- The largest difference in fuel use is by LH drivers in the 55 to 65 mph speed range. These drivers used 8 percent less fuel in treatment compared to baseline. Furthermore, the amount of fuel consumed in this speed range by the LH drivers is more than all P&D drivers across all speeds and all LH drivers at speeds below 55 mph combined. LH drivers in the 55 to 65 mph speed range consume approximately 63 percent of all fuel used by all drivers at all speeds.

Table 20: Total Fuel Used as a function of Speed Range and Driver Category

Speed Range	Baseline Fuel Used, Liters	Treatment Fuel Used, Liters	Time* Hours	Fraction (Trmt/Base)
	Pick-up and Delivery			
25 to 35 mph	189.1	186.7	8.9	0.99
35 to 45 mph	264.8	254.1	15.4	0.96
45 to 55 mph	93.9	97.6	5.1	1.04
55 to 65 mph	172.1	175.1	7.5	1.02
All P&D	719.8	713.5	36.9	0.99
	Line-haul			
25 to 35 mph	67.4	67.8	2.1	1.01
35 to 45 mph	110.3	105.8	4.2	0.96
45 to 55 mph	332.5	324.8	11.8	0.98
55 to 65 mph	2156.7	1981.0	77.7	0.92
All LH	2666.9	2479.3	95.7	0.93
	Both P&D and Line-haul			
25 to 35 mph	256.5	254.4	11.0	0.99
35 to 45 mph	375.1	359.8	19.6	0.96
45 to 55 mph	426.4	422.4	16.8	0.99
55 to 65 mph	2328.7	2156.1	85.2	0.93
All	3386.7	3192.8	132.6	0.94

*Represents time in Baseline or Treatment

Table 21 is a summary of the fuel used in all treatment modes combined with an estimate of the change in fuel consumption when comparing baseline and treatment (LPM Active only) for each driver, driver category and all drivers. The left side of the table shows fuel used for all LPM modes (Inactive, Driver, Active, and Transitioning) along with cruise control engaged and speed below 25 mph (the LPM minimum speed threshold). All of these columns are mutually exclusive.

The three columns in the center-right of the table show the fuels used in baseline and treatment (LPM Active) and are based on the sampling strategy outlined earlier in this report. These columns represent the estimated effect of the LPM system on fuel consumption for each driver and driver category. The Difference (Diff) is the estimated total fuel saved (positive number) or consumed (negative number) as a result of the LPM control.

The left-most two columns in the table show the fraction of fuel saved or consumed due to the LPM control normalized by the Equal Time baseline fuel used in the LPM Act column or by the Total fuel used value for all treatment modes. These two columns illustrate the importance of the denominator in calculating the potential benefits of the LPM on fuel consumption. The most direct comparison between a system with or without LPM is derived by comparing treatment and baseline under the same conditions and for an equal amount of exposure. This comparison shows the maximum benefit of the system and can be used to derive the additional benefit from changing LPM Inactive and Driver mode into the LPM Active state or by expanding the LPM functionality to include cruise control engaged driving (although, implied, the actual effect of the LPM on driving with cruise control was not measured in this study). However, a fleet may want to know the overall effect of the LPM on fuel used. To address this issue, the potential fuel consumption change by the LPM must be compared to the total fuel used by all drivers in the fleet (all treatment modes).

Based on

Table 21 and the analysis done earlier in this report, the conclusions related to the LPM and fuel consumption are:

- The LPM system did decrease fuel consumption for five of eight P&D drivers.
- The LPM system did decrease fuel consumption for all LH drivers.
- The effectiveness of the LPM at reducing fuel consumption appears to be a function of vehicle speed. The greatest benefit coming at speeds above 55 mph.
- The overall reduction in fuel consumption was 2 percent for all drivers and 3 percent for LH drivers when considering the fleets' total fuel used during the treatment period.
- The overall reduction in fuel consumption was 6 percent for all drivers and 7 percent for LH drivers when comparing similar driving conditions in the baseline and treatment (LPM
- Active only) exposure periods (i.e., no cruise control engaged, speed above 25 mph and no brake or turn-signal activity).

Table 21: Fuel Used in Treatment and Savings Fraction for LPM Active and all Treatment Exposure

Individual Driver Fuel Used Summary												
	Fuel Used, Liter (All Treatment modes)							Fuel Used, Liter			Fraction	
								Equal Time				
Drvr	Spd < 25 mph	Cruise Eng	LPM InAct	LPM Driver	LPM Act	LPM Trns	Total	Base	Trmt	Diff	LPM Act	Trmt Total
1	84	3	51	5	47	1	191	54	47	7.0	0.13	0.04
2	82	0	6	24	82	2	196	82	82	-0.1	0.00	0.00
3	33	0	11	5	44	1	93	49	44	5.3	0.11	0.06
4	106	0	9	32	68	1	215	78	68	10.1	0.13	0.05
5	104	1	5	16	157	2	285	160	157	2.6	0.02	0.01
6	68	209	123	17	84	2	503	96	84	11.7	0.12	0.02
7	76	135	86	23	118	0	439	101	118	-17.6	-0.17	-0.04
8	119	88	383	198	113	3	904	100	113	-12.6	-0.13	-0.01
101	41	180	133	9	172	21	557	198	172	26.2	0.13	0.05
102	72	468	73	22	817	13	1465	838	817	21.2	0.03	0.01
103	66	81	683	43	648	68	1588	716	648	68.4	0.10	0.04
104	56	584	387	101	595	12	1735	658	595	63.0	0.10	0.04
105	45	1488	4	26	247	2	1812	256	247	8.8	0.03	0.00
Driver Category and All Driver Summary												
P&D	671	437	673	320	713	12	2826	720	713	6	0.01	0.00
LH	280	2802	1281	200	2479	115	7158	2667	2479	188	0.07	0.03
All	952	3238	1954	520	3193	127	9984	3387	3193	194	0.06	0.02

Driver Subjective Questionnaire Results

All drivers who participated in the study were volunteers and monetarily compensated for their participation. There were four four-week study sessions. Each four-week session was divided into a two-week baseline period, followed by a two-week treatment period during which the LPM was activated.

Each study session began with an initial briefing to describe the study to a group of drivers, to answer any questions they had about the study and to collect written informed consent from each driver in accordance to the University of Michigan Institutional Review Board's (IRB) guidelines for research involving human subjects. Drivers who consented to participate were then assigned by Con-way Operations Personnel to each of the two trucks in driver-pairs—a pickup-and-delivery (P&D) driver for daytime driving, and a long haul (LH) driver for night driving.

Study Sessions

At the beginning of each study session drivers were reminded that data on their driving would be collected along with video recordings of their activities. In addition, signs were conspicuously posted in each cab to advise both drivers and passengers that their activities were video-recorded.

At the start of the treatment phase, drivers were also given a refresher briefing about the LPM operation before the system was activated. In addition, each driver was given the opportunity to test-drive the tractors accompanied by UMTRI and Eaton Corporation personnel. At the end of the treatment phase, drivers were paid for their participation and asked to complete a short questionnaire about their participation in the study.

Questionnaire Design

The questionnaire was designed to efficiently solicit drivers' opinions in three primary topic areas: training, LPM control functions, and display interface. The basic construction used a 5-level Likert[4] [19] scale in which drivers were asked to indicate their level of agreement with a series of statements about their participation in the field test. On average drivers were able to complete the survey in 10 to 15 minutes.

Training

Adequacy of training was first assessed to determine if drivers believed that they were given a clear explanation of how the LPM operated. Opinions were solicited in four training areas: knowledge about how the system operated, how the LPM engaged, how to override the LPM, and how the system would help drivers conserve fuel. A facsimile page of this part of the questionnaire is shown in Figure 40.

A breakdown of each driver's response for the first item, opinion that the operation of the LPM was easily understood, is shown in Figure 41. Note that the figure shows the breakdown between P&D drivers and LH drivers. Overall, both groups of drivers either strongly agreed or agreed that they understood the LPM operation.

[4] A Likert scale is an ordered qualitative scale commonly used in surveys where respondents are asked to provide an ordinal rating. It is named after Rensis Likert who pioneered the method in 1932 [11].

Similarly, drivers were in general agreement that they understood how the system engaged (Figure 42), and how to override the system (Figure 43). There seemed to be less clear agreement among the drivers about their understanding about how the LPM assisted drivers in saving fuel, although 10 drivers agreed or strongly agreed that they understood that the system would help safe fuel, while 3 drivers neither agreed nor disagreed.

Look-ahead System (LPM) Questionnaire

Subject ID:______________________ Date:__________

Rate the degree to which you agree with the following statements as follows:

Strongly Agree	Agree	Neither Agree Nor Disagree	Disagree	Strongly Disagree

Training:

1) The training I received on the Look-ahead system was easy to understand in each of the following areas:	Strongly Agree	Agree	Neither	Disagree	Strongly Disagree
a. How the system works	☐	☐	☐	☐	☐
b. How to engage the system	☐	☐	☐	☐	☐
c. How to temporarily override the system	☐	☐	☐	☐	☐
d. How the system helps drivers save on fuel	☐	☐	☐	☐	☐

Additional comments: ______________________________

____

Figure 40: Survey items related to the training drivers received about the LPM system

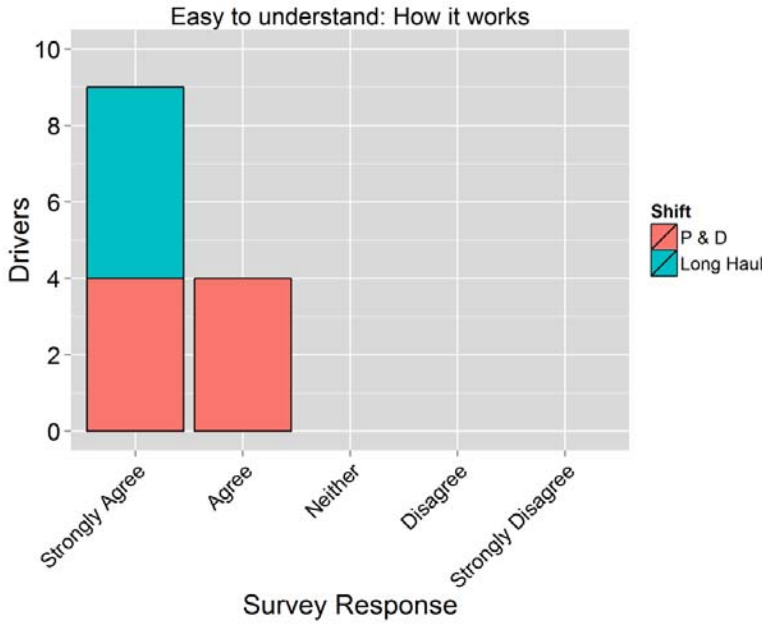


Figure 41: Drivers' level of agreement that the system was easy to understand

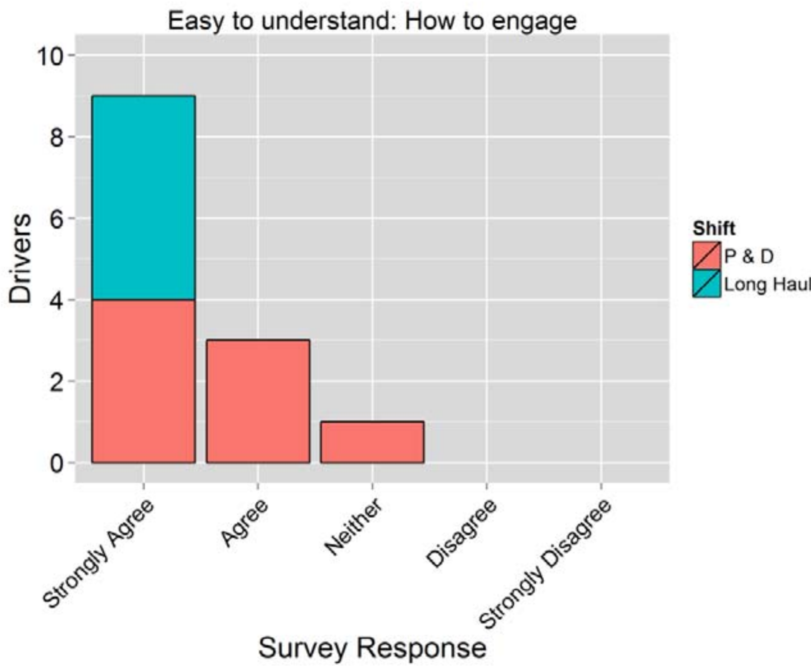


Figure 42: Drivers' level of agreement that how the system engaged was easy to understand

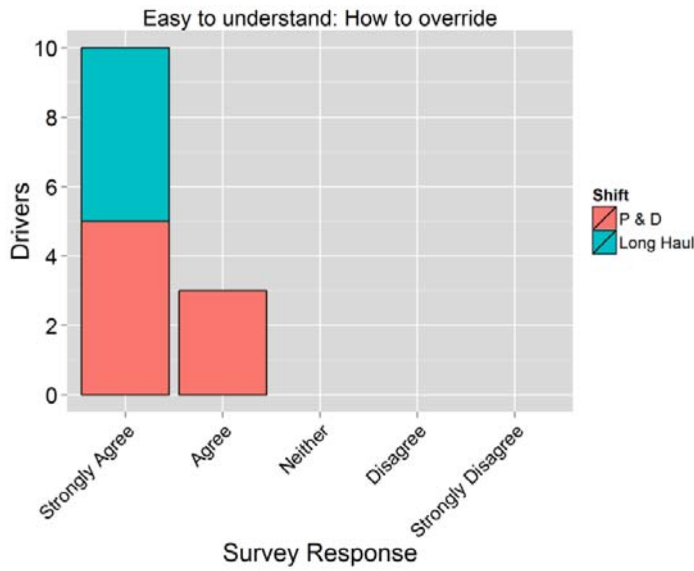


Figure 43: Drivers' level of agreement that how to override the LPM was easy to understand

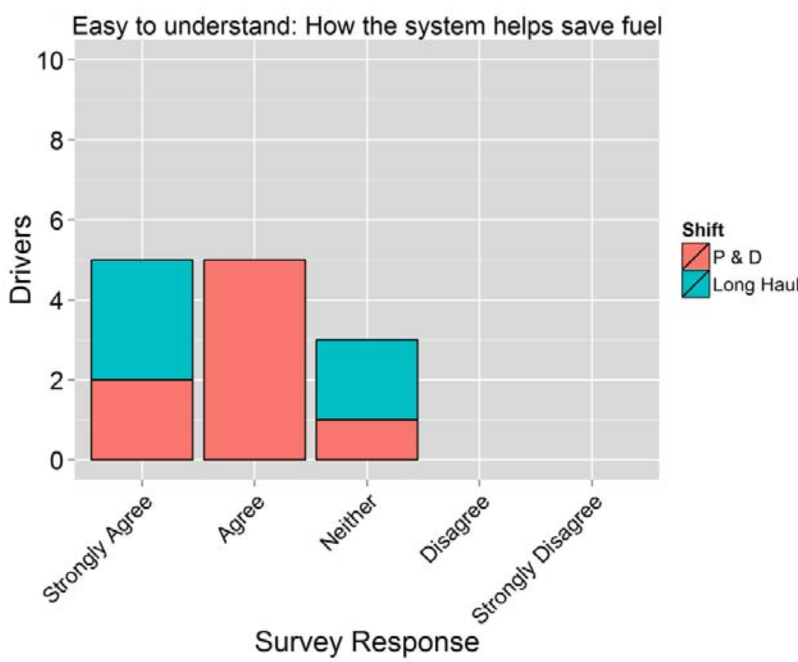


Figure 44: Drivers' level of agreement that how the system helps to save fuel was easily understood

Control Functions

In this series of questions, drivers' opinions were surveyed about the operation of the LPM with respect to their ability to distinguish when the driver versus the LPM was in control, whether they agreed that the system imposed sensible limits on their driving, whether they felt their in-vehicle workload was reduced, their opinion about fuel savings on freeways and city streets, and whether the drivers believed they had learned anything from the LPM about driving in a fuel-efficient manner. A facsimile of the control part of the questionnaire is provided in Figure 45.

Overall, 12 drivers either agreed or strongly agreed that it was easy to distinguish who had control authority, one LH driver strongly disagreed with this statement (shown in Figure 46). No further comments were registered by this driver.

There was less agreement among the drivers about whether the limits imposed by the LPM consistently made sense (Figure 47). Eight drivers agreed or strongly agreed that imposed limits made sense, while three drivers disagreed and two drivers neither agreed nor disagreed. There were anecdotal reports from two of the LH drivers that the LPM did not always appear to register changes in speed limit in a timely fashion. In particular, these drivers noted that the system seemed to delay recognizing increases in speed limit, although it is likely that drivers may have been biased to notice delays in speed limit increases versus decreases.

Ten drivers reported either no impact on workload or a reduction in workload; three drivers disagreed or strongly disagreed that the LPM reduced workload (shown in Figure 48).

Drivers generally seemed to agree that the LPM saved fuel on both freeways and city streets, although there appeared to be less certainty about city streets (Figure 49).

Six drivers thought that the LPM may have helped them develop a better fuel-saving driving style, while five drivers were neutral and two disagreed (shown in Figure 50).

Control:

Rate the following statements about the control functions:	Strongly Agree	Agree	Neither	Disagree	Strongly Disagree
2) I had no difficulty distinguishing when the Look-ahead system was controlling my speed and when I was in control	☐	☐	☐	☐	☐
3) The limits the system imposed on power made sense after I drove it awhile	☐	☐	☐	☐	☐
4) The system limits on power helped reduced may workload behind the wheel	☐	☐	☐	☐	☐
5) The Look-ahead helped me save fuel: On freeways:	☐	☐	☐	☐	☐
6) On city streets:	☐	☐	☐	☐	☐
7) The Look-ahead system helped me develop a better fuel saving driving style	☐	☐	☐	☐	☐

Additional comments:____

____

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Figure 45: Survey items related to the drivers' opinions about how the LPM controlled the truck

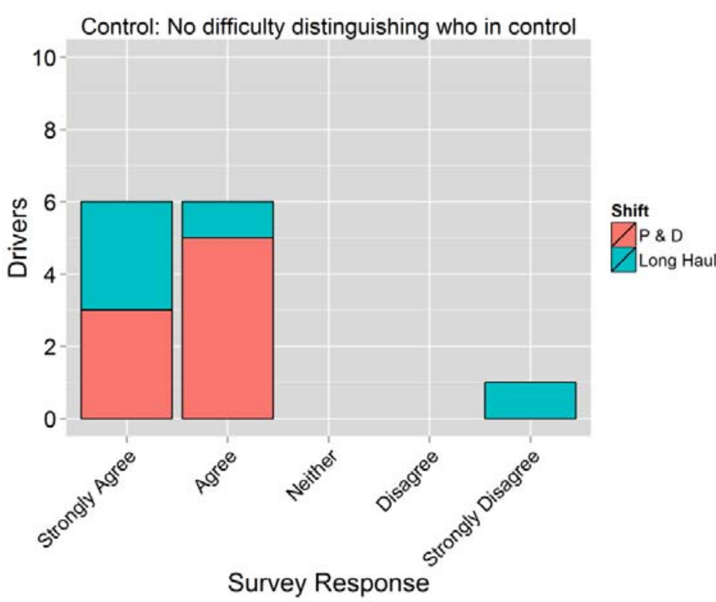


Figure 46: Drivers' level of agreement that they had no difficulty distinguishing whether the driver or the LPM was in control

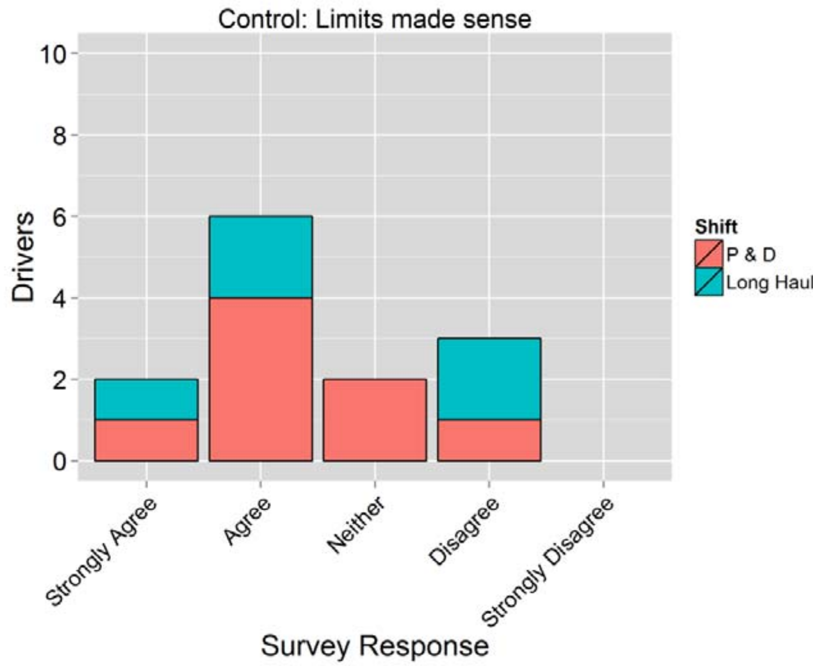


Figure 47: Drivers' level of agreement that the limits imposed by the LPM made sense

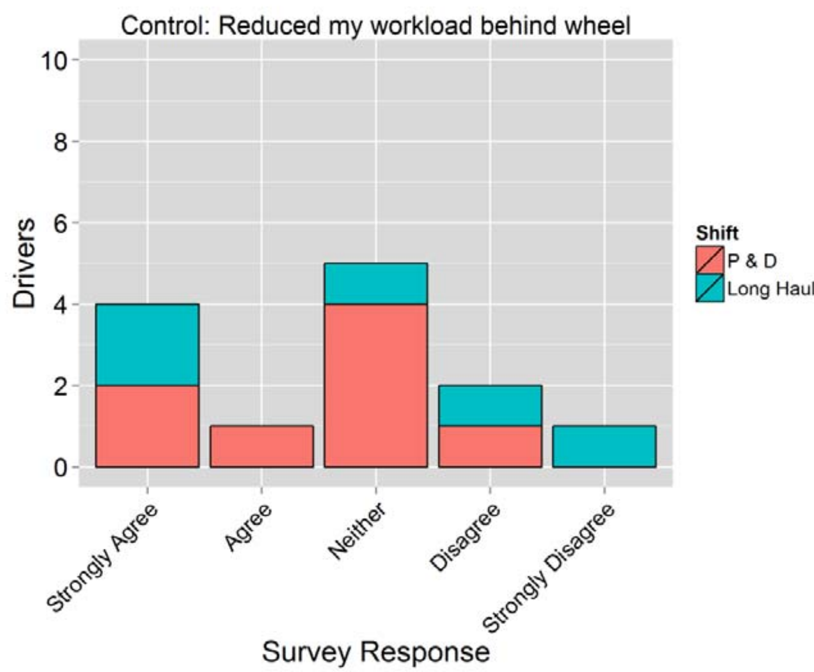


Figure 48: Drivers' level of agreement that the LPM helped reduce driver-workload

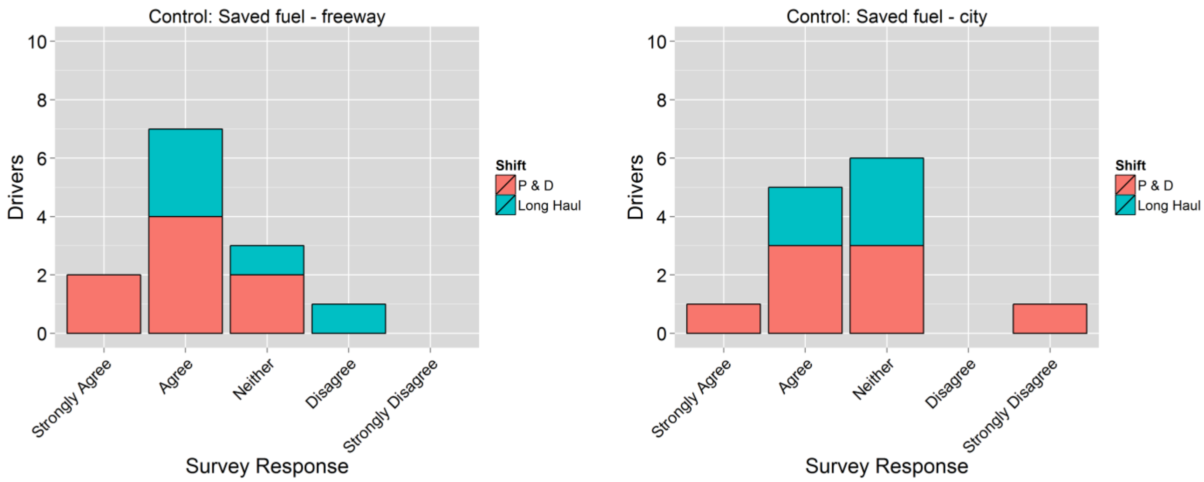


Figure 49: Drivers' level of agreement that the LPM was perceived to have saved fuel on the freeway (left) or on city streets (right)

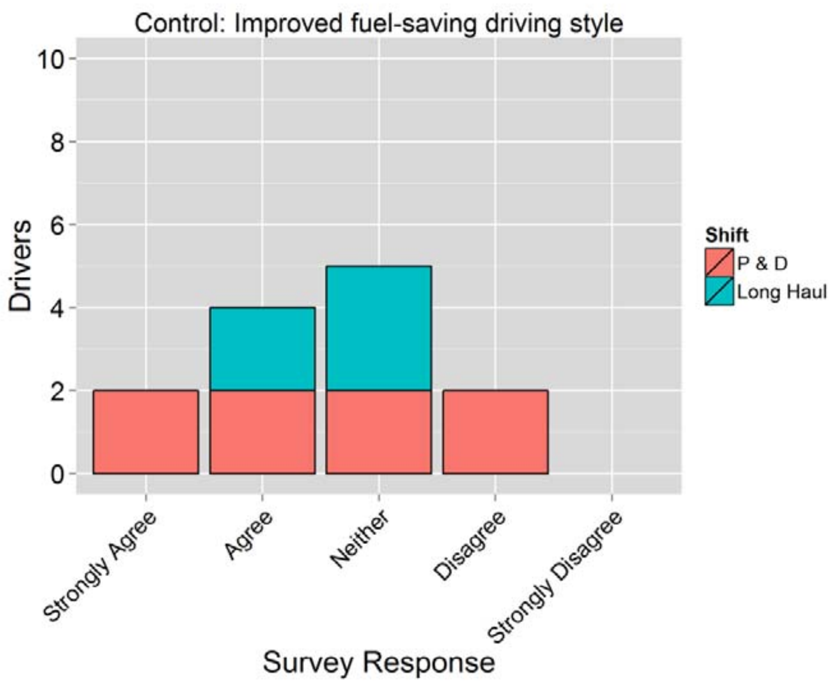


Figure 50: Drivers' level of agreement that the LPM helped them develop a better fuel saving driving style

Display Characteristics

In this series of questions, drivers' opinions about the specific display interface to the LPM were solicited. In particular, drivers were asked to rate their level of agreement with statements declaring that the display was easy to understand, and that the display clearly reflected roadway conditions, that the information displayed was useful. This latter item was also followed up by a request to identify which information drivers believed to be most useful. Drivers were also asked whether they thought the display was unnecessary, and whether they believed other information might be more useful. A facsimile of the display segment of the questionnaire is provided in Figure 51. Overall, all 13 drivers agreed that the display was easy to understand (Figure 52).

There was less agreement, however, with respect to whether the display status clearly reflected road conditions: six drivers agreed that it did, while three drivers disagreed with the statement and four were neutral on the subject (Figure 53). Similar concerns are reflected in many of the survey comments at the end of each section

Nine of the drivers agreed that the information presented on the LPM display was useful; two were neutral on the subject, one driver disagreed, and another driver omitted responding (Figure 54). Four drivers commented directly on the information they found useful, identifying the indicators that forward vehicles were present, turn approaches, and speed limits. One driver mentioned that he could often identify the roadway condition directly, before the display indicated it.

Drivers' opinion about the necessity of the LPM display seemed to be evenly distributed across the response range: four drivers agreed that it was necessary, three disagreed suggesting the display was not necessary, and the remaining six drivers were neutral (Figure 55).

Finally, drivers were asked to rate their agreement with the suggestion that other information might be more useful to display. The intent of this question was to solicit additional suggestions from the drivers about other possible pieces of information that might be found helpful. Only four drivers agreed that other information might be more useful (Figure 56). Of these, only two drivers suggested alternative display information: a GPS navigation system and information about the detected forward vehicle's travel speed.

Display:

Rate the following statements about the display system:	Strongly Agree	Agree	Neither	Disagree	Strongly Disagree
8) The Look-ahead display was easy to understand.	☐	☐	☐	☐	☐
9) The Look-ahead status information clearly reflected roadway conditions.	☐	☐	☐	☐	☐
10) The Look-ahead system presented useful information.	☐	☐	☐	☐	☐
[Please identify most useful information]					
11) The Look-ahead display was not necessary.	☐	☐	☐	☐	☐
12) I think other information might be more useful to display.	☐	☐	☐	☐	☐
[Please identify other information here]					

Additional comments: ____

____

Figure 51: Survey items related to the drivers' opinions about the LPM display interface

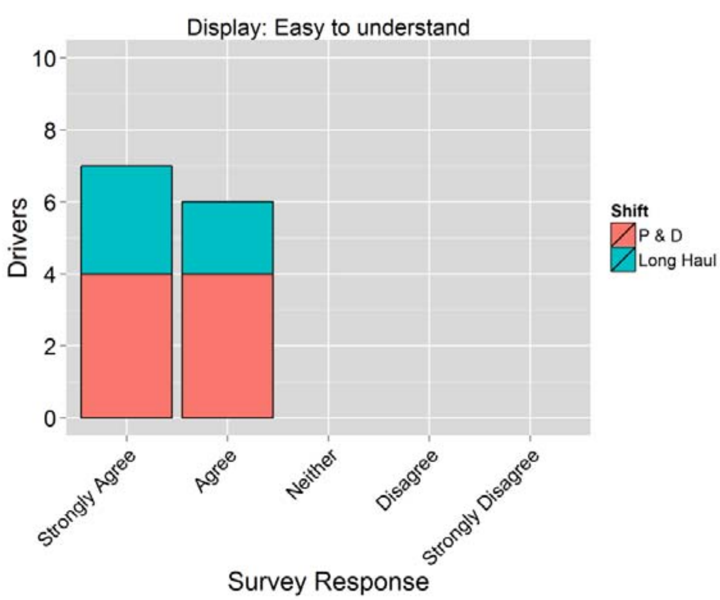


Figure 52: Drivers' level of agreement that the LPM display was easy to understand

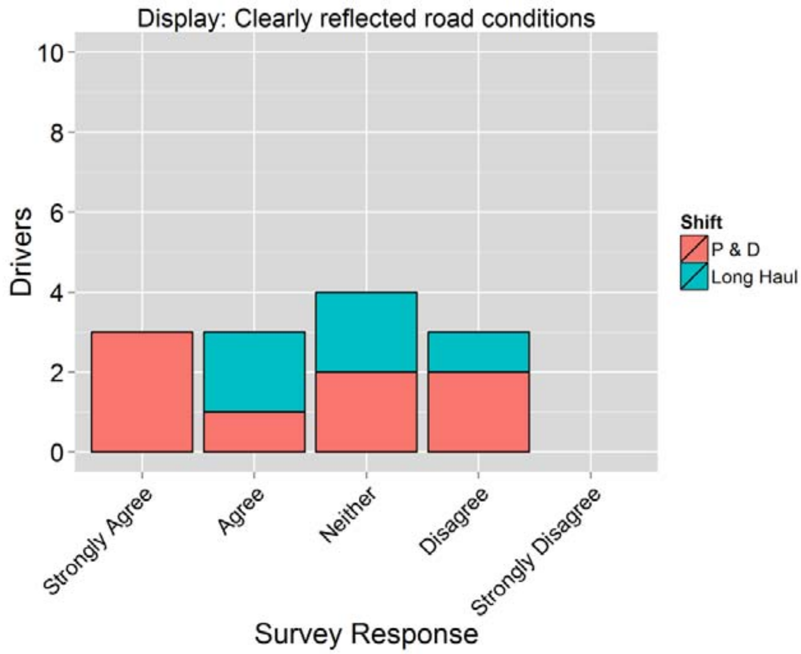


Figure 53: Drivers' level of agreement that the LPM display status clearly reflected road conditions

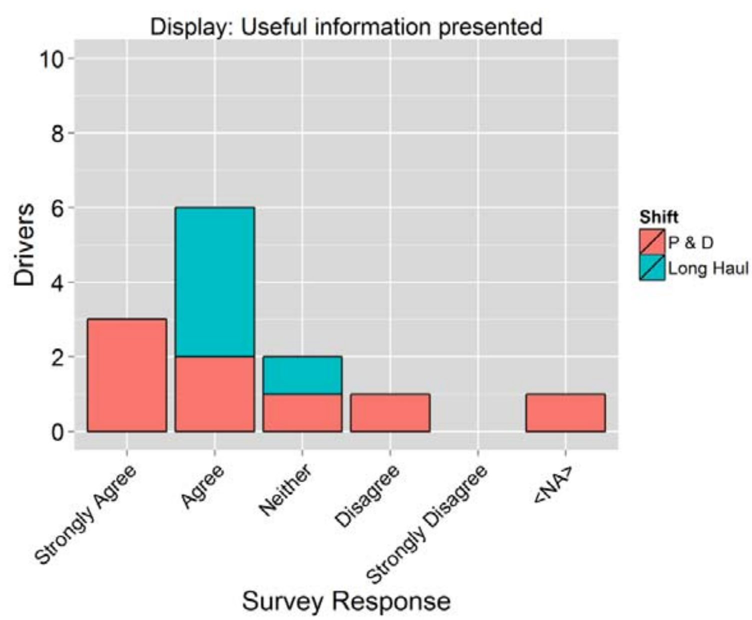


Figure 54: Drivers' level of agreement that the information presented on the DVI display was useful

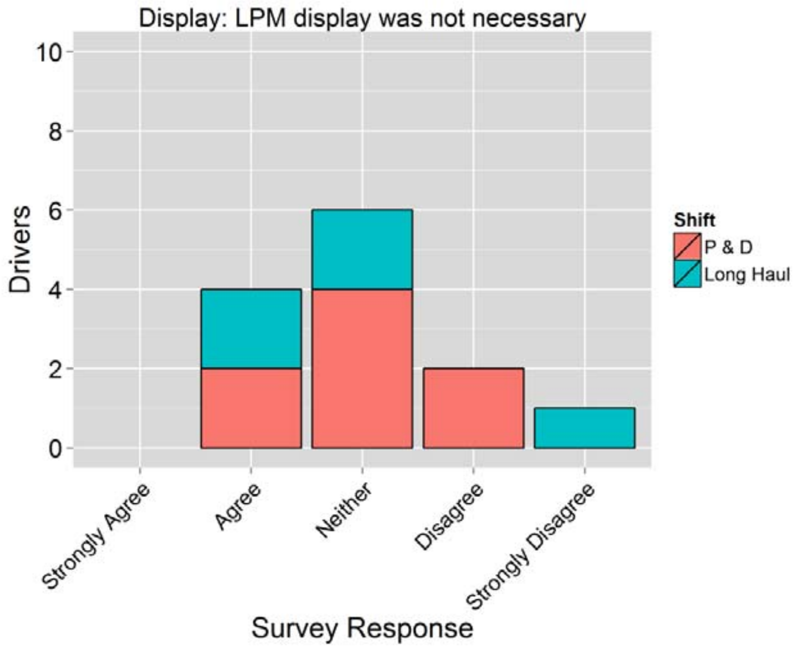


Figure 55: Drivers' level of agreement that the LPM display was not necessary

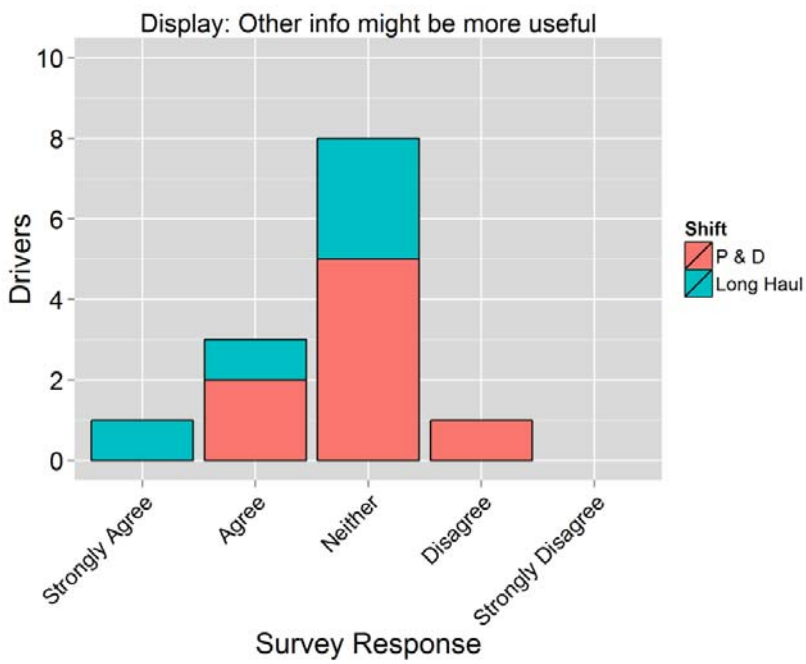


Figure 56: Drivers' level of agreement that other information on the LPM display might be more useful

ORNL's Evaluation Report

Background

The Eaton Look-Ahead Powertrain Management (LPM) system aims to improve fuel efficiency by providing real-time feedback to the driver and optimizing the powertrain control using GPS route information, digital map and real-time traffic information obtained from on-board sensors as well as V2V and V2I communications. The fuel efficiency benefits of this technology are strongly related to changes in the vehicle drive cycle that occur as a result of the driver feedback. In this way, the system attempts to improve driver behavior and minimize the effect of driver reactions to external conditions on the vehicle fuel efficiency. This approach offers a benefit for fuel savings with significant potential. However, evaluation of the resulting fuel saving benefits is challenging since the effectiveness of the system depends rather strongly on the external conditions present while driving in real-world situations, which cannot be controlled during testing. Varying traffic conditions, temperature and other weather conditions, changes to the vehicle load, vehicle maintenance issues, and other factors will all affect the actual fuel consumption achieved, and the LPM system functions by modifying the driver's speed control behavior in a manner that will optimize the truck fuel economy. Fuel economy differences that are less than several percent are very challenging to accurately quantify, and without a highly controlled and repeatable experimental approach, such as the SAE J1321 fuel test, results are subject to scrutiny. For a real-world evaluation of the system, an in-fleet evaluation must be conducted to obtain realistic results, which effectively rules out the use of a very controlled test procedure. Instead, measurements of the vehicle operation during naturalistic operating conditions were conducted. Such a real world evaluation is necessary for evaluating ITS technologies of this type, but quantifying the fuel savings is particularly challenging due to the high variability of operating conditions and the presence of external variables that can influence measurement results. Evaluations performed in real-world usage thus normally require extensive data to be collected, with measurements of several vehicles over extended time periods, in order to characterize and assess the external factors and accurately quantify the fuel savings that a technology provides.

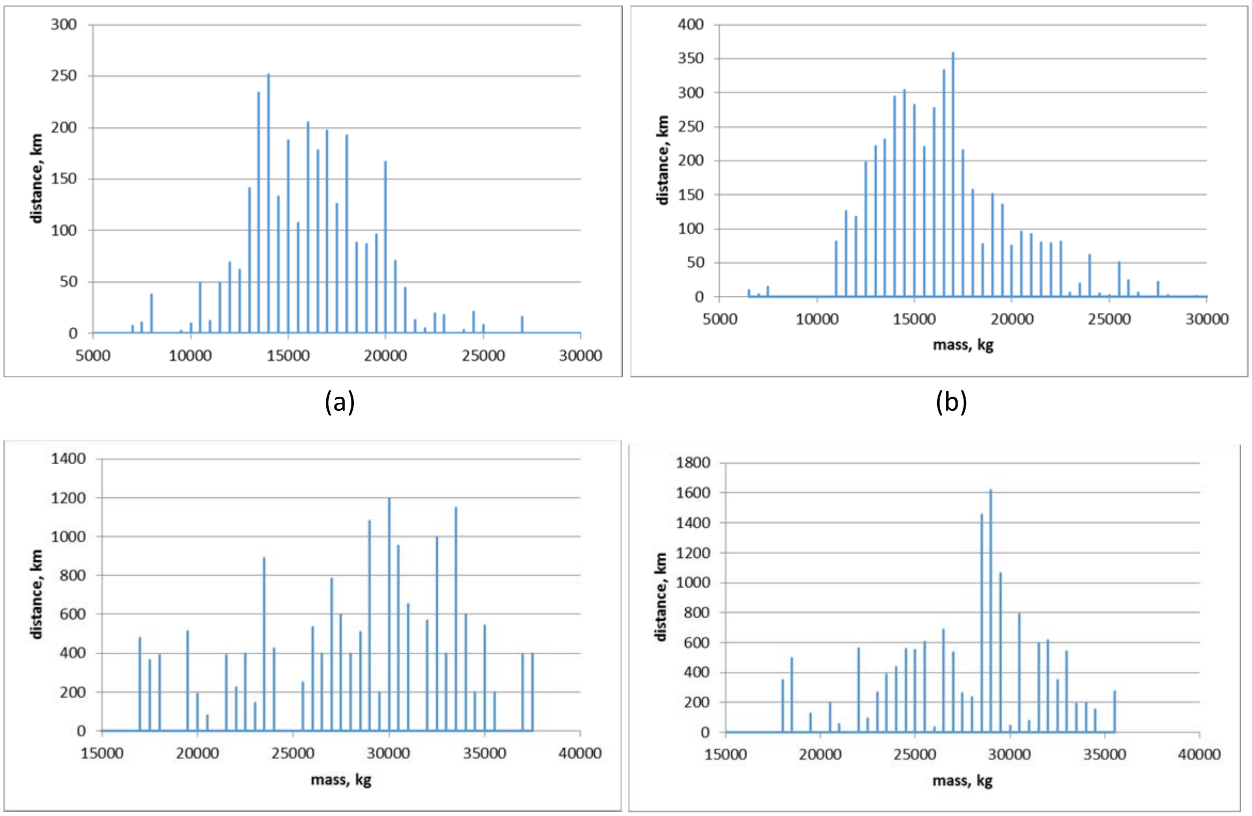
For this project, an alternate approach to direct fuel measurement was followed to evaluate the fuel saving benefits of the LPM system by using a rigorous analysis of the differences in drive cycles followed when the LPM system is enabled vs. disabled. ORNL was tasked to evaluate the LPM system to quantify the fuel efficiency benefits that can be expected when using the technology in normal real-world usage. The approach used for ORNL's fuel assessment consists of a statistical evaluation of the measured vehicle drive cycles followed when the LPM system is "on" and "off," and developing representative drive cycles that characterize the difference in behavior for the two scenarios. Based on the drive cycle characterization, a tractive energy and fuel consumption analysis is subsequently used to quantify the fuel savings benefits achieved with the LPM system. This approach aims to eliminate many of the errors and uncertainties associated with a direct fuel measurement and serves as a validation of the direct measurements that were also conducted during the project.

Drive Cycle Analysis

Based on the issues discussed above concerning measurement challenges, an alternative approach was followed for characterizing the LPM fuel efficiency benefits using complementary information to the direct fuel consumption measurements. The approach consists of a detailed analysis of the differences in driving behavior with the LPM activated vs. deactivated, and vehicle performance modeling using Autonomie software as a final step to evaluate the fuel savings due to the LPM operation. Analysis of the tractive energy corresponding to the measured drive cycles was also used to develop a better understanding of the energy consumption from the vehicle in the two operating modes evaluated (with the LPM system either enabled or disabled).

To characterize the drive cycles for the two operating modes, the bivariate distribution of speed and acceleration was developed for each case. Since the load plays a primary role in fuel consumption and the load carried varies rather significantly during normal trucking operations, all results were evaluated using selected ranges of load. (This restricted ORNL's analysis to consider only that test data for which the vehicle mass was available.) The operations in line haul (LH) vs. pickup & delivery (P&D) usages were also treated separately. Figure 57 shows the distribution of masses contained in the measured data for the LPM enabled and LPM disabled data for both LH and P&D applications. The data is presented in terms of the mass vs. the distance traveled at discrete mass levels (500 kg bins were used). The distance weighted average mass values were 16307, 16637, 28565, and 27819 kg, for the P&D LPM enabled, P&D LPM disabled, LH LPM enabled, and LH LPM disabled cases, respectively. The median values of the mass (based on the mass value for each trip) were 16653, 16525, 29303 and 28630 kg, respectively. The mass ranges for the drive cycle analyses were selected to help ensure that a reasonable number of files were available within each data set considered and to keep the span of each range relatively consistent. For this analysis, it was decided to exclude data files for very short trips since they did not contain a broad range of acceleration and velocity data that is representative of each application. For P&D, trips were only considered if the distance traveled exceeds 1 km, and for LH only trips greater than 10 km were included. It was found that dividing the range in two for both P&D and LH showed relatively consistent characteristics in the distribution data.

For the drive cycle analysis, each set of distribution data was evaluated using a bivariate histogram, and the histograms from different operating conditions were assessed to identify differences in the vehicle operation across each mode. Figure 58 to Figure 69 show comparisons of the bivariate histograms for LPM enabled and disabled modes for the LH and P&D applications over two different mass ranges.



(a) (b) (c) (d)

Figure 57: Distribution of vehicle mass for (a) P&D LPM enabled, (b) P&D LPM: disabled, (c) LH LPM enabled and (d) LH LPM disabled cases

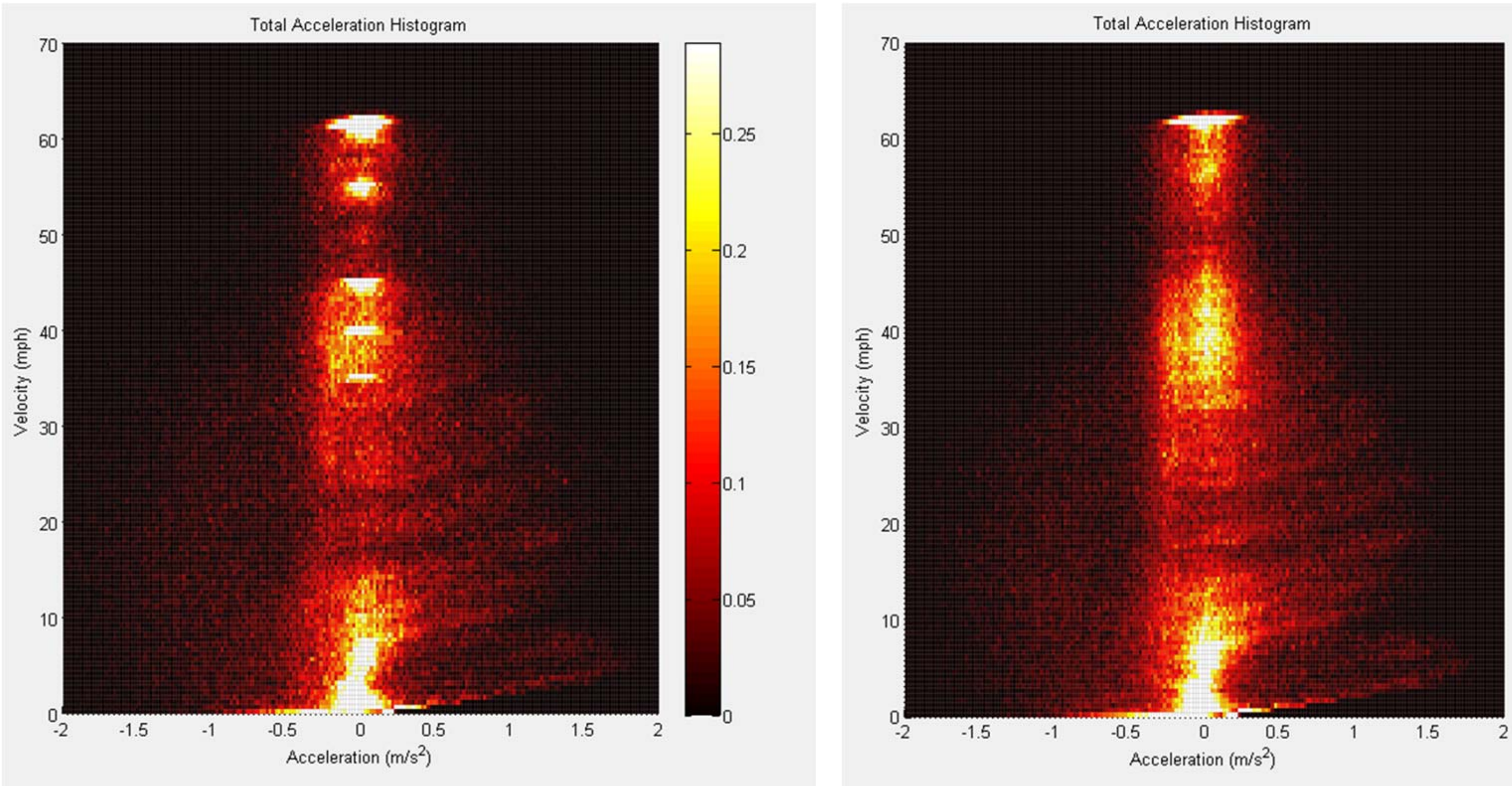
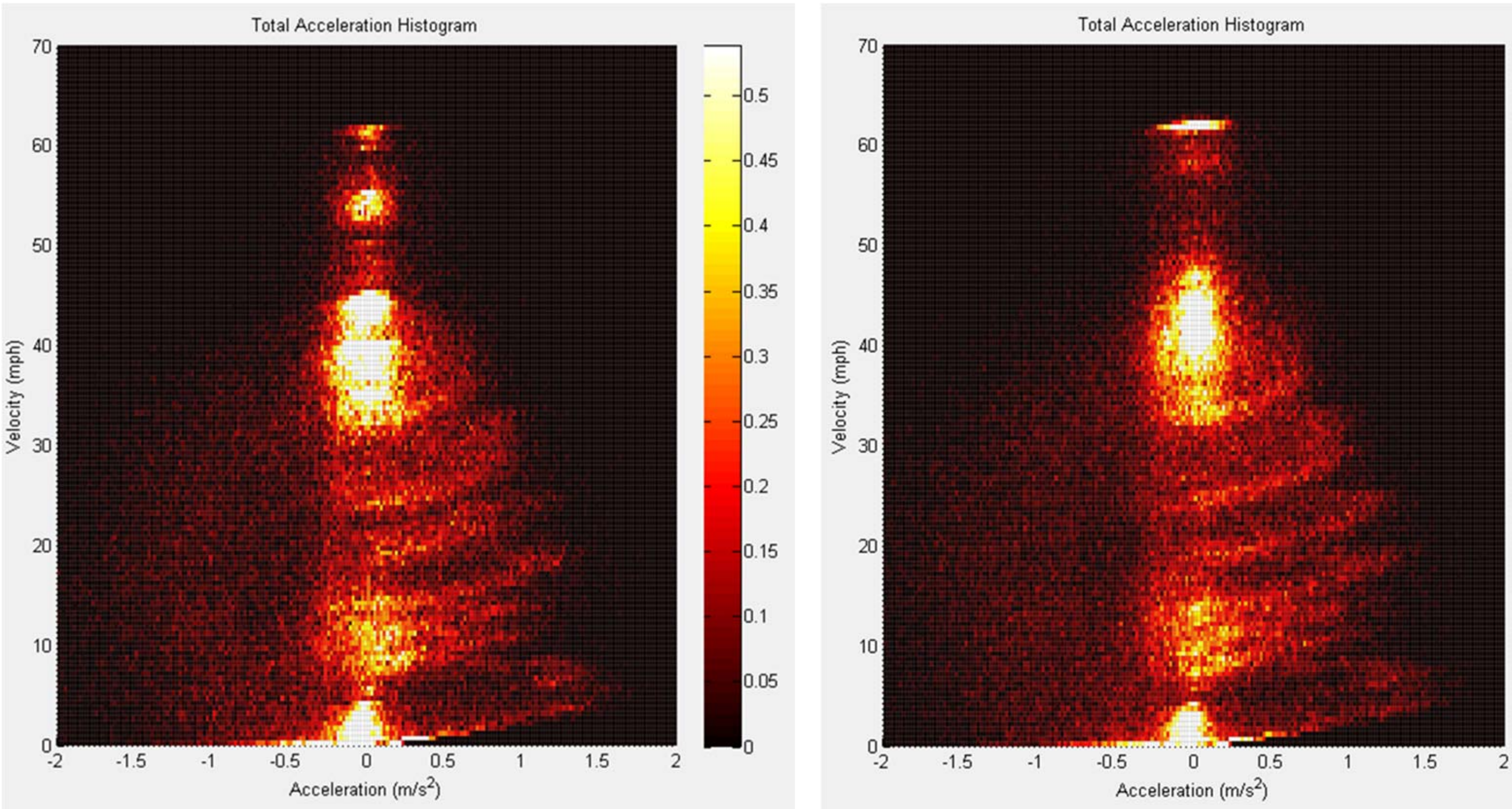
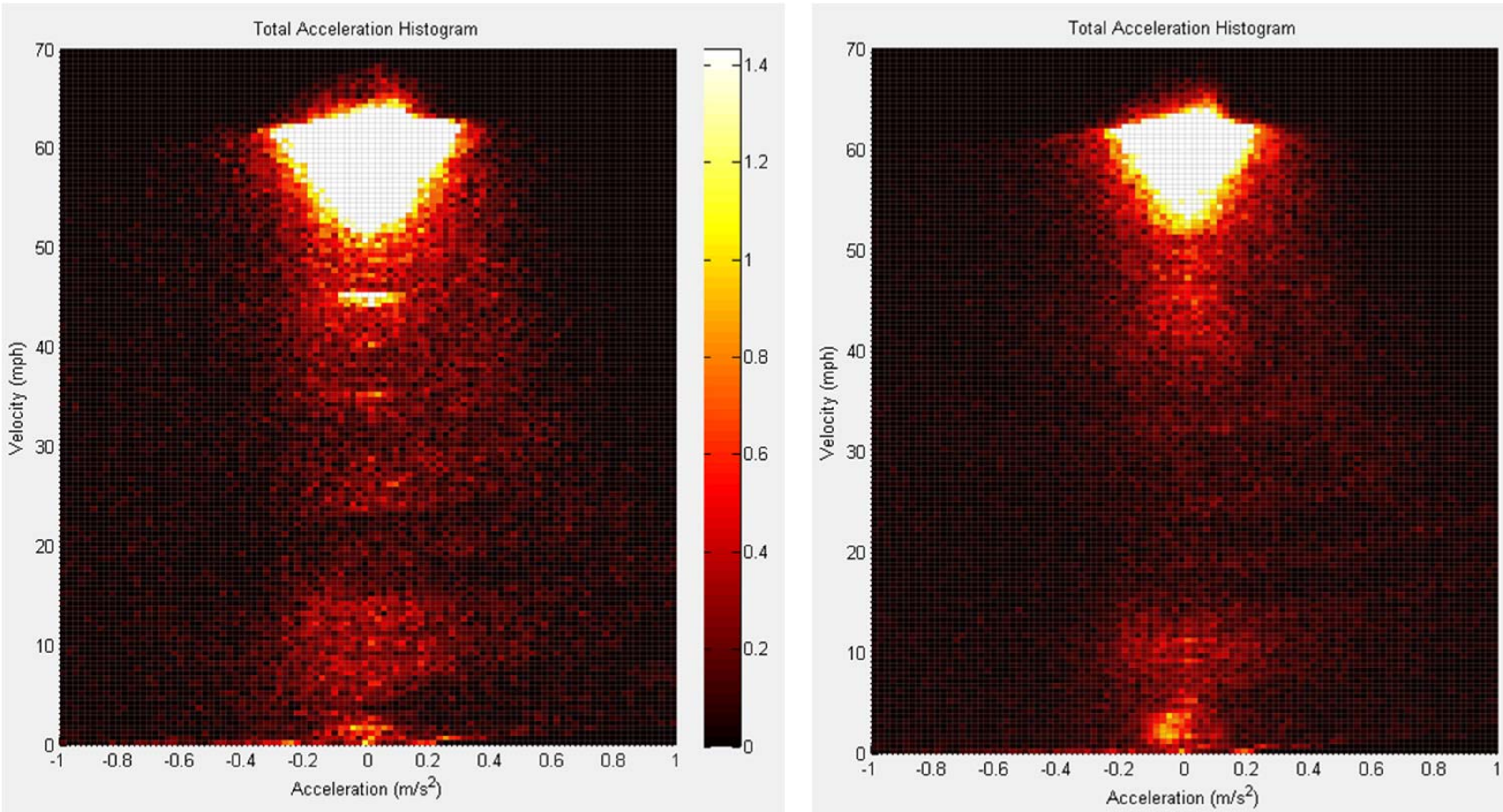


Figure 58: Acceleration-velocity bivariate histograms for the P&D application for masses in the range 8000-16,500kg for the (a) LPM enabled and (b) LPM disabled operation. Trip lengths only over 1 km in length were included in the analysis.



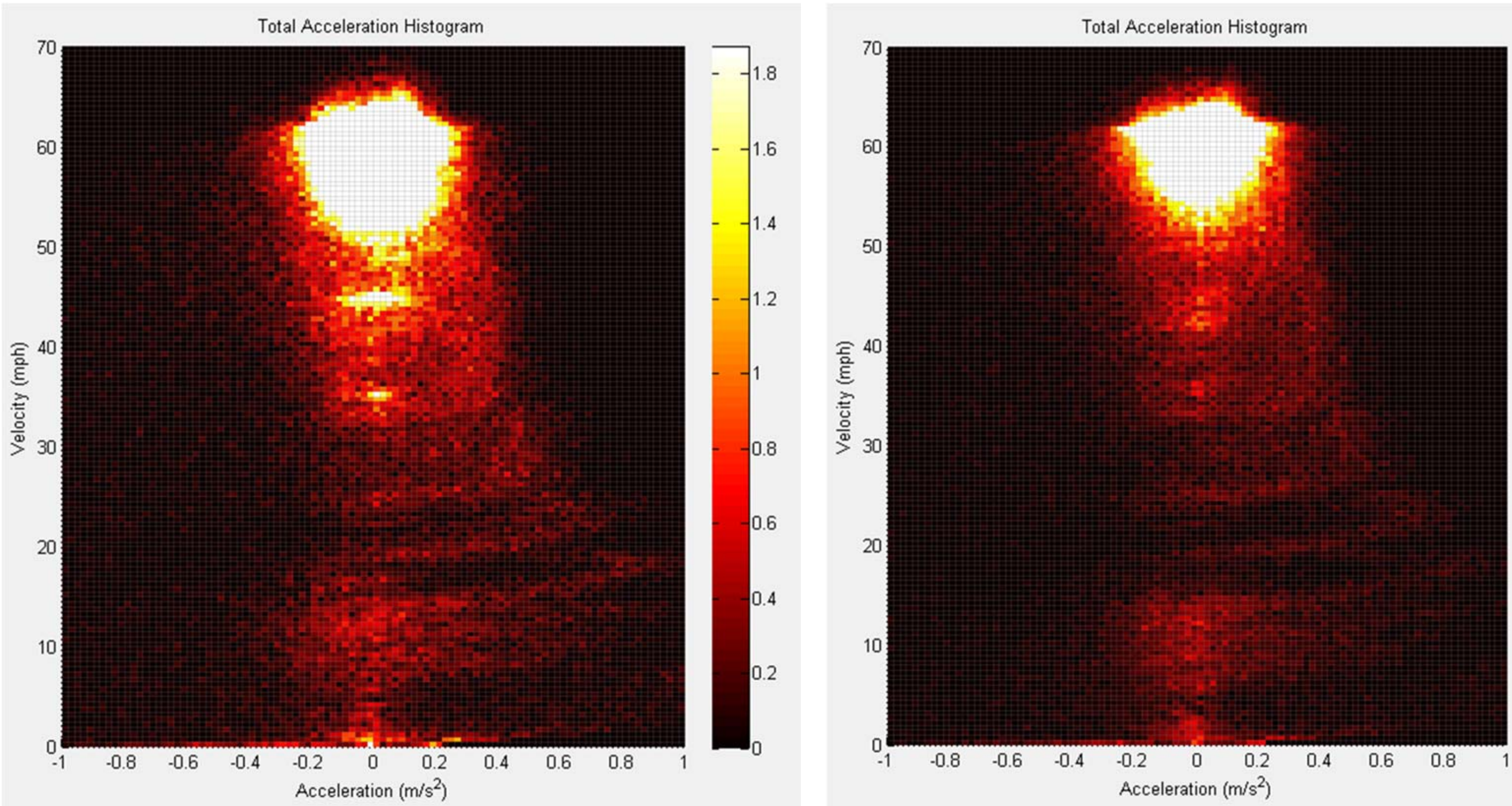
(a) (b)

Figure 59: Acceleration-velocity bivariate histograms for the P&D application for masses in the range 18000-22,000kg for the (a) LPM enabled and (b) LPM disabled operation. Trip lengths only over 1 km in length were included in the analysis.



(a) (b)

Figure 60: Acceleration-velocity bivariate histograms for the LH application for masses in the range 18000-28,000kg for the (a) LPM enabled and (b) LPM disabled operation. Trip lengths only over 10 km in length were included in the analysis.



(a) (b)

Figure 61: Acceleration-velocity bivariate histograms for the LH application for masses in the range 28000-38,000kg for the (a) LPM enabled and (b) LPM disabled operation. Trip lengths only over 10 km in length were included in the analysis.

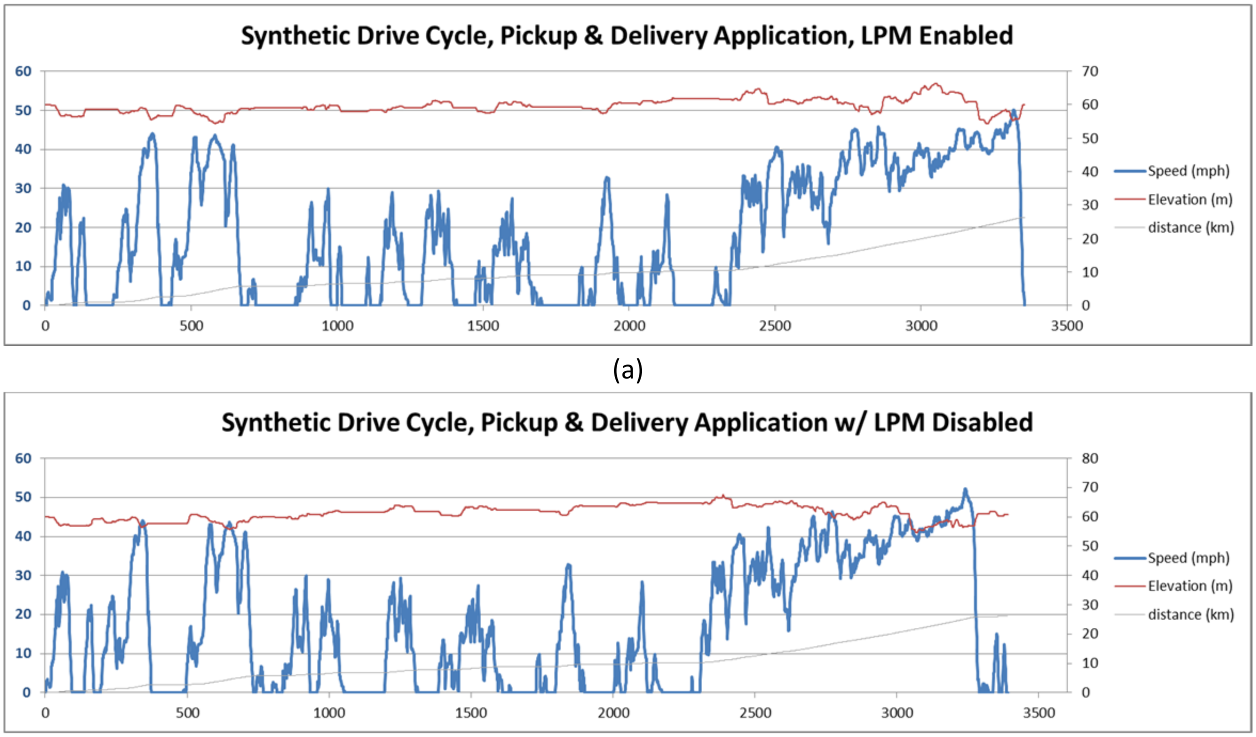
For the P&D data evaluated, it was observed that there was a fairly large quantity of data for travel occurring at speeds over 55 mph, which is not typical of the P&D usage. This data corresponds to trips to the delivery area before and after the local deliveries comprising the P&D operation are made. Since it was desired to consider only the P&D operations, the data for speeds over 60 mph was removed from the analysis. For the LH data, there was one driver whose data showed a consistently higher level of accelerations than all other drivers, but only a small fraction of the data containing vehicle mass for this driver corresponded to when the LPM was disabled. Since almost all of the available data for this driver was for the LPM enabled mode , the results were somewhat skewed toward higher accelerations for the LPM enabled case and to minimize this effect it was decided to reject the data for this driver in the LH selections.

The bivariate histogram data visually shows a regular difference between the LPM on and off cases for all of the scenarios considered. With LPM enabled, there tends to be a more discrete set of speed levels driven as opposed to a more uniform distribution in speed for the LPM disabled data sets. The LPM system limits the vehicle speed to the speed limit, and this reduces speed variations around the speed limit in those cases. Since the histogram captures all of the speed and acceleration histories within the distribution, the influence of other differences in the vehicle operation on the energy requirements for the vehicle will also be captured in the more detailed speed analysis of the data set.

Somewhat surprisingly, there was not much difference in the levels of accelerations observed for different mass ranges for each application. Although a lower mass allows the vehicle to accelerate more rapidly, the maximum accelerations and velocities remain relatively constant among the two vehicle mass cases considered for both the LH and P&D applications. In LH, there is a more triangular shape to the data for the lower mass case (Fig. 4, as compared to Fig. 5), showing that accelerations are perhaps slightly increased with the lower load.

The main objective for developing the speed-acceleration bivariate distribution data was to enable quantification of the fuel consumption differences between the LPM enabled vs. LPM disabled operations. To this end, ORNL’s Duty Cycle Generation (DCGen) Tool (further details of which are available in an ORNL report [20]) was used to create a synthetic drive cycle for the P&D application data. Data for the 18,000-22,000 kg mass range was selected for this analysis, although the trends in the data were observed to be quite similar in both cases. It was initially planned to develop the synthetic drive cycles for both the LH and P&D applications, but this part of the research proved to be exceedingly time consuming and only the two P&D cases were completed. The synthetic drive cycle creation consists of generating a drive cycle with a nearly identical statistical content for the accelerations and velocities as the measured data represented in the bivariate histogram, but the synthetic cycle is developed to have a length of 20-60 minutes, which allows it to be used in vehicle performance modeling software such as Autonomie, GT Drive, or AVL Cruise. The data contained in each bivariate histogram represents tens to hundreds of hours of driving, so it would not be possible to use the complete set of original data in a vehicle model. The synthetic drive cycle therefore is intended to be very representative of the complete data set but is a synthesis of that data, hence the term “synthetic drive cycle.” The DCGen Tool assists the user to select segments of drive cycles from the original data set to build up a cycle with the same statistical content of speeds and accelerations as the original drive cycle. With the tool, drive cycle segments are selected one by one to build up the same histogram as contained in the original bivariate histogram representing the measured data. After an appropriate set of drive cycle segments are selected, they are then patched together and endpoints joined to form a continuous synthetic drive cycle. Grade data from the original cycle is also included in the creation of the synthetic cycle, so the elevation variations should also be quite similar to what is contained in the original data. Although this process is simple in concept, it is a very time-consuming process to perform the synthetic cycle development in practice. To improve efficiency, it is planned to fully automate this process in future research.

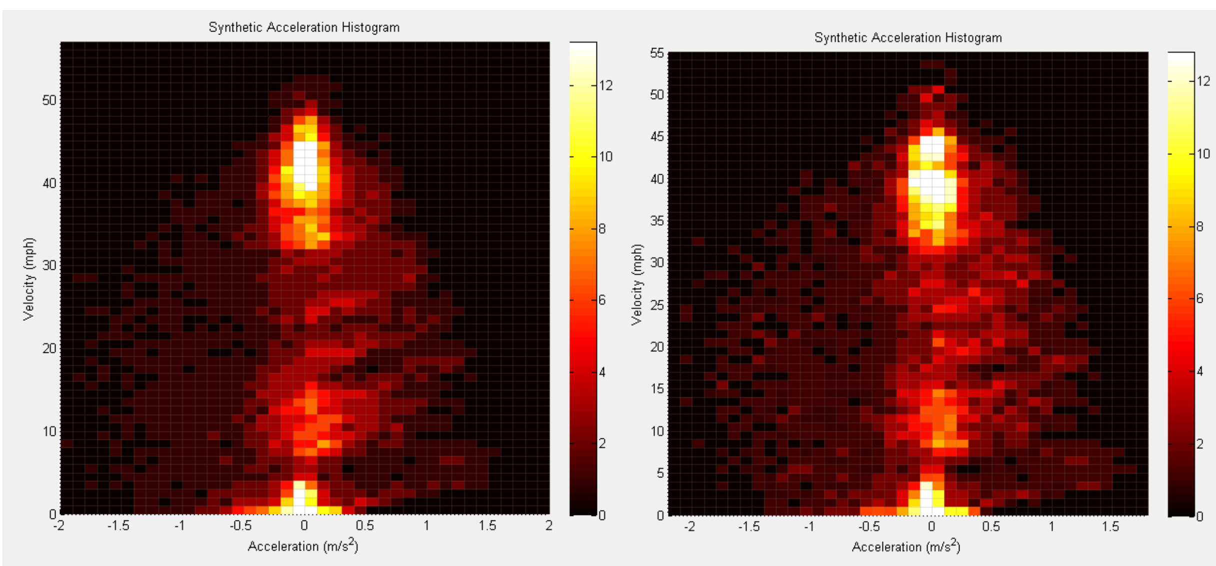
For this analysis, the P&D LPM enabled synthetic drive cycle was created first. Bin sizes for the acceleration and speed used in the cycle development were 0.1 m/s^2 and 1 mph, respectively. In order to save time in the second synthetic cycle creation, instead of starting from scratch with the LPM disabled case, the segments selected in the first case were used as a starting point for the second synthetic cycle development. The LPM disabled histogram was loaded into the DCGen Tool from the initial analysis and segments that were not present in the second cycle were removed while missing segments needed to match the new targeted histogram were selected and added to the original cycle. In both the LPM enabled and disabled cases, the difference between the original cycle histogram, after scaling to the shorter cycle length, and the synthetic cycle for any bin in the histogram was less than two seconds, and the difference was less than 1s for over 95% of the bins. The resulting synthetic cycles for both cases are shown in Figure 62, and the final bivariate histograms are presented in Figure 63. This accuracy in matching the synthetic cycle histograms to the original histograms ensures that they are very good approximations to the acceleration and speed data of the original measurements, although it should be noted that the bin size used for the synthetic cycle creation was less refined than what was shown in the histograms shown in Figure 62 and Figure 63.



(a)

(b)

Figure 62: Synthetic drive cycles for (a) the P&D LPM enabled and (b) P&D LPM disabled cases



(a) (b)

Figure 63: Bivariate histograms for the synthetic drive cycles for (a) the P&D LPM enabled case and (b) P&D LPM disabled case

With the synthetic cycles generated as they were, using one cycle as the starting point for the other, it is very apparent how very similar the two usages are. Although differences between the two drive cycles can be identified visually under careful examination, a casual comparison will likely conclude that the two cycles are identical. This small difference in usage highlights the challenge faced in accurately quantifying the difference in fuel consumption between the two cases. The approach of simulating the fuel economy based on the usage may seem less appropriate than simply evaluating the measured fuel consumption. However, this comparison of drive cycles underscores the validity of the approach. Uncertainties and variations associated with the fuel measurements are greater than those of the vehicle speed measurement. And while the modeling of fuel economy may not be accurate in an absolute sense, it is fully repeatable and the differences in calculated fuel economy on a relative basis are expected to be quite reasonable for a specified usage. The subtle differences in the drive cycle are adequately evaluated in the fuel economy simulation so that the modeled *difference* in fuel consumption can be more reliable than testing a vehicle on the two very similar cycles.

Once the two synthetic cycles were created, they were used to estimate the difference in fuel economy between the two cases using Autonomie vehicle performance software[5]. A truck model developed by ORNL was modified to have vehicle parameters corresponding to those of the Con-way vehicles tested in the study. The fuel economy results from the Autonomie simulation is shown in Table 24, along with tractive energy calculations for the drive cycle corresponding to the same vehicle modeled. The predicted fuel consumption values of 56.37 L/100km and 57.37 L/100km for the LPM enabled and LPM disabled cases, respectively, represent a fuel savings of 1.74% for the usage with the LPM enabled in the P&D application. Note that this corresponds only to the usage evaluated for the P&D application, i.e. it applies to the mass range from 18,000-22,000 kg for the P&D application.

[5] See http://www.autonomie.net/ for details of the Autonomie vehicle simulation software.

Table 22: Autonomie fuel consumption predictions and driving tractive energy calculations for the P&D LPM enabled and P&D LPM disabled synthetic drive cycles

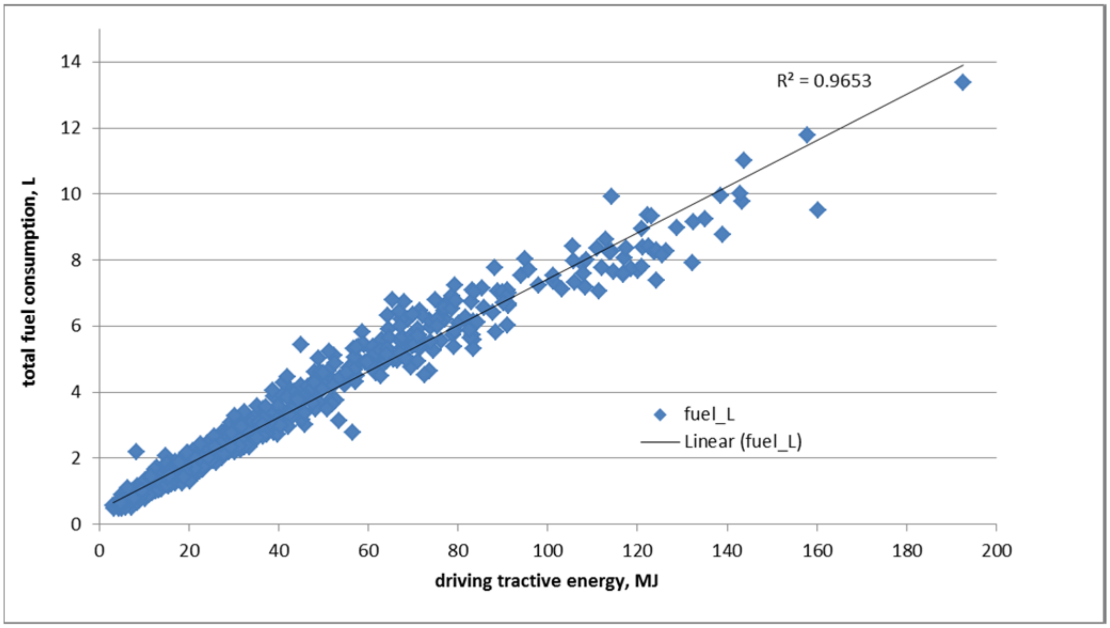
	P&D LPM enabled	P&D LPM disabled
Cycle distance, km	26.04	25.81
Autonomie estimated total fuel, L	1467.83	1480.94
Fuel consumption, L/100km	56.37	57.37
Mass specific fuel consumption, L/100km/ton	2.89	2.94
Driving tractive energy (MJ)	118.32	119.54
Mass specific driving tractive energy, MJ/100km/ton	23.30	23.75

Tractive energy assessments

Due to resource limitations and the time required to create each synthetic drive cycle, the synthetic drive cycles were developed only for the two P&D cases (LPM enabled and disabled) presented above, and the fuel economy evaluation using the synthetic drive cycle analysis was thus only completed for the comparison of these two P&D cycles. A second but simpler evaluation approach was pursued in an effort to estimate the fuel savings associated with the LPM system for the LH application also. Vehicle fuel consumption is known to be a relatively strong function of driving tractive energy,[6] and this correspondence is even more valid when usages are similar, so that the range of engine operating conditions and the associated engine efficiency do not differ substantially. Since the usage for the LPM enabled and LPM disabled operations are indeed very similar, we should expect that the fuel savings provided by the LPM could be reasonably estimated from differences in the driving tractive energy.

Figure 64 shows the correspondence between the driving tractive energy and fuel consumption for both the P&D and LH applications. The high correlation between these is the basis for evaluations of fuel economy based on the driving tractive energy, which can be determined more reliably from the drive cycle measurements than the fuel consumption itself.

[6] See reference 1 for additional discussion of tractive energy and fuel consumption.

(a)


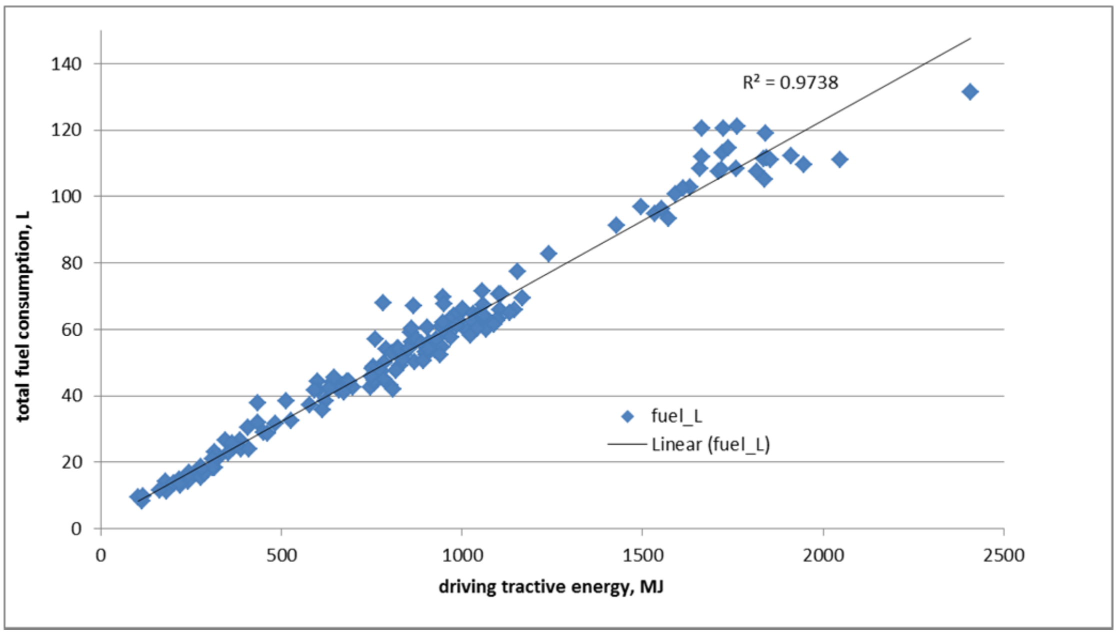
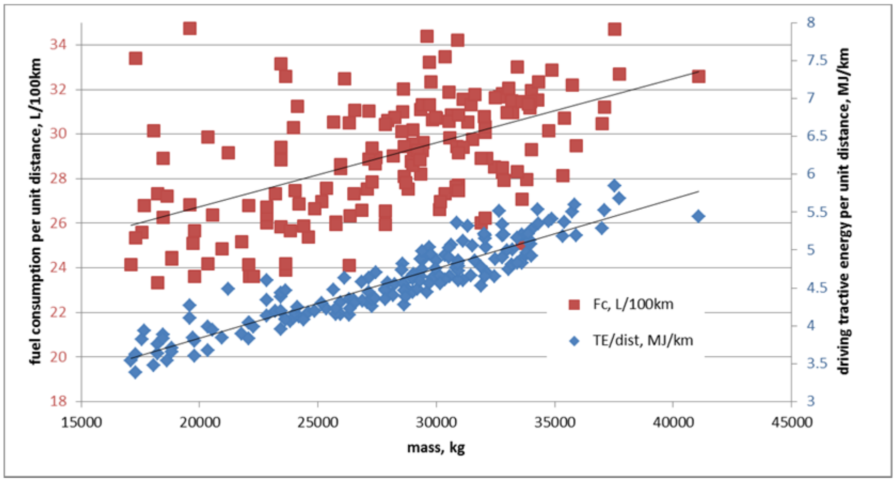
(b)


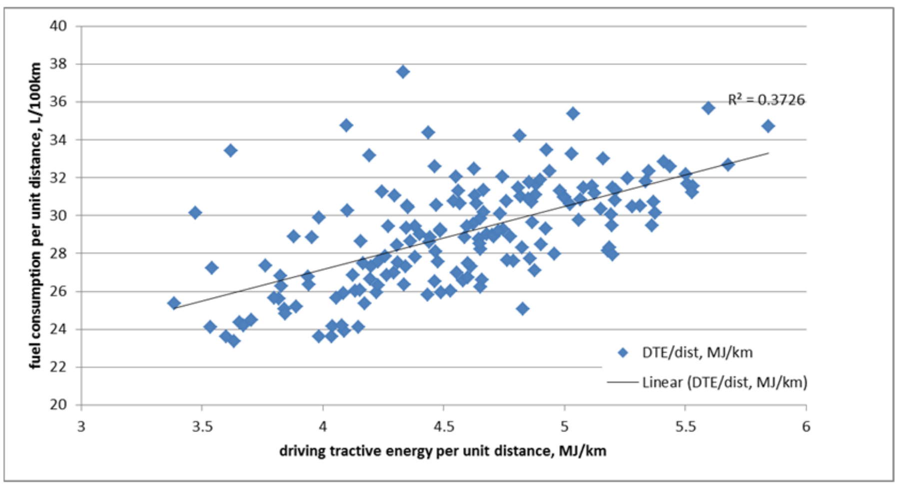
Figure 64: Fuel consumption for each trip plotted vs. the driving tractive energy for (a) P&D usage and (b) LH usage.

Since the mass and distance vary considerably from trip to trip, it is important to relate the tractive energy and fuel consumption to these values to correctly estimate the fuel consumption for a specific usage. Fuel efficiency, as measured using a L/100km (or gallon/mile) metric, is most closely related to the tractive energy per unit distance traveled.

Figure 65(a) shows a comparison of the measured fuel consumption per unit distance and the calculated driving tractive energy per unit distance as a function of the vehicle mass, for all of the LH data for which mass is available. It is apparent that more scatter exists in the data for the fuel consumption data but the common trend is clear. The correlation between the two data sets is relatively low, however, with $R^2 = 0.373$, as shown in Figure 65 (b).



(a)

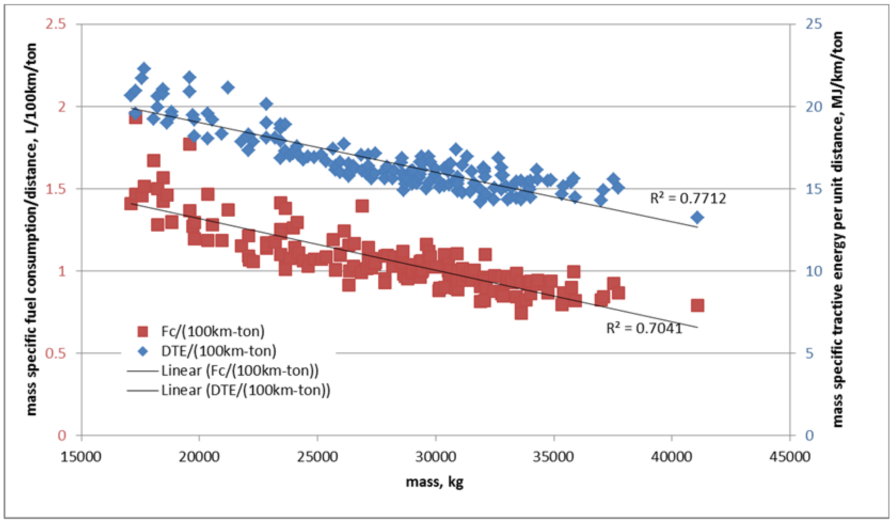


(b)

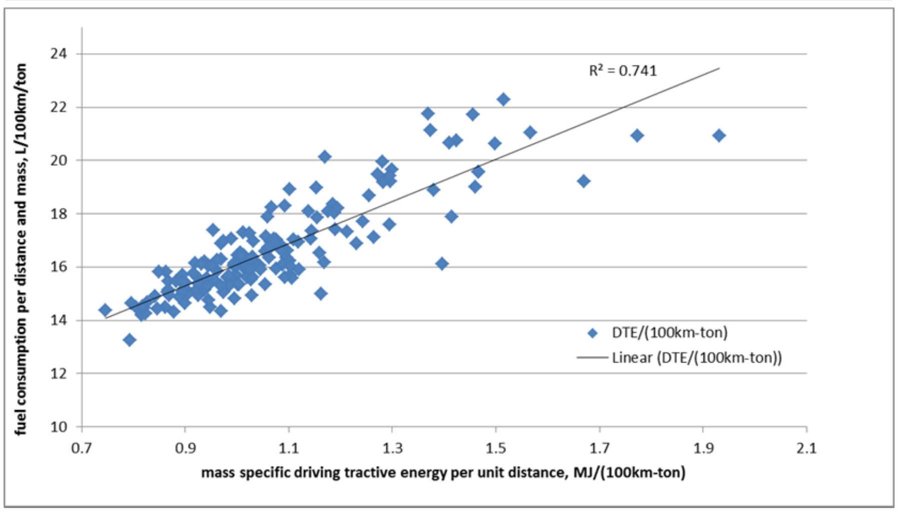
Figure 65: Comparison of the trip measured fuel consumption per unit distance traveled and the driving tractive energy per unit distance. (a) shows the comparison as a function of the vehicle mass while (b) shows a cross-plot of the two quantities.

Dividing the tractive energy per unit distance and the fuel consumption per unit distance by the vehicle mass to obtain mass specific quantities results in a much better correlation, with the R^2 value nearly doubled to 0.741, as shown in Figure 66 (b). Although this correlation is not at the same level as for the relationship between the driving tractive energy and fuel consumption, it still indicates that nearly 75% of the variation in the fuel consumption on a mass and distance specific basis is explained by the corresponding tractive energy value. The high correlations

(>0.95) for the total fuel consumption and driving tractive energy show that other differences in the individual drive cycles for each trip account for most of the remaining variation.



(a)



(b)

Figure 66: Relationship between the mass specific fuel consumption per unit distance and the MSDTE per unit distance, plotted (a) as a function of the mass and (b) showing the overall correlation between the two variables, for the LH application.

This shows that the mass specific fuel consumption per unit distance traveled (L/100km/ton) varies approximately linearly with the mass specific driving tractive energy (MSDTE) per unit distance traveled, which is the driving tractive energy divided by the vehicle mass and the distance of the trip. Based on this relationship for the LH data, the tractive energy analysis can be used to provide a first order estimation of the differences in fuel consumption for the two different usages corresponding to LPM enabled vs. disabled. Since the fuel consumption is normalized by the distance and the mass in this case, it provides a means to compare the different usages even though the average mass and distance were not the same for the LPM enabled and LPM disabled cases.

The DCGen Tool was used to calculate the tractive energy for each data file using the mass data for each particular trip along with parameter values for the aerodynamic drag coefficient (0.65), vehicle frontal area (7.43), and coefficient of rolling resistance (0.0072) that are appropriate for the test vehicles. The tractive energies were summed for all trips and an average value of the MSDTE/100km/ton for the combined data was calculated using the total distance traveled and the distance-weighted average mass of the vehicles in the aggregated data.

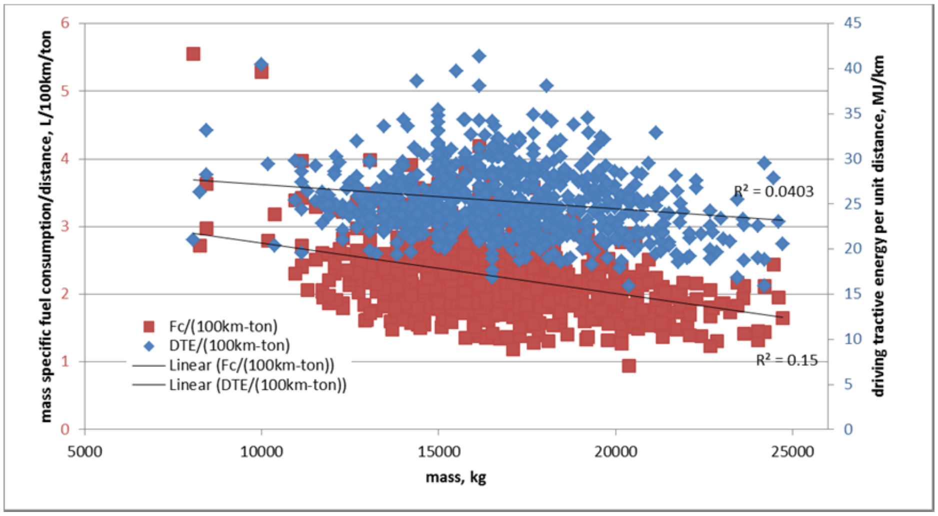
The overall average of MSDTE/100km was calculated for all of the trips for the LH usage within the 28,000-38,000 kg mass range. Table 23 shows the calculations, including results using the measurement data for the P&D application. The end result is an estimated fuel savings of approximately 1.2-1.4% for the LH application for the 28,000-38,000 kg mass range.

Table 23: MSDTE/km calculations based on the measured speed data

	P&D LPM enabled	**P&D LPM disabled**	**LH LPM enabled**	**LH LPM disabled**
Average mass (kg)	19452	19670	31941	30811
Total distance, km	614.2	698.1	8459.6	7780.5
Sum of the driving tractive energy (MJ)	2756498	3330905	41435253	37257044
MSDTE/km, kJ/(km-kg)	0.2307	0.2426	0.1533	0.1554
% reduction in MSDTE/km with LPM enabled	4.89%	--	1.33%	--
MSDTE/km for the synthetic drive cycles	0.2309	0.2353	--	--

It was expected that the same analysis applied to the P&D application would confirm the results of the synthetic drive cycle analysis. However, as seen in Table 23, the fuel savings calculated with this method is about 4.89% as compared to only a 1.74% fuel savings predicted using the synthetic drive cycles and the Autonomie simulations. The MSDTE/km value for the synthetic cycles differed from that calculated using the average of measured cycle data by 0.3% and 2.2% for the P&D LPM enabled and LPM disabled cases, respectively. It was expected that the tractive energy of the synthetic drive cycle would closely match that of the measured data, given the close similarities in the usage for the synthetic drive cycles. Since the speeds and accelerations differ much more between trips for the P&D application than for the LH application, there is considerably higher variation in the MSDTE/km values among trips for the P&D application than for LH. The result is that the impact of mass and distance on the tractive energy are strongly mixed with the drive cycle effect on a trip by trip basis, and the trip data does not allow the impact of these variables to be accurately estimated with the tractive energy analysis. This is evidenced by the low correlation between the MSDTE per unit distance and the mass specific fuel consumption per unit distance, as shown in Figure 67.

(a)



(b)

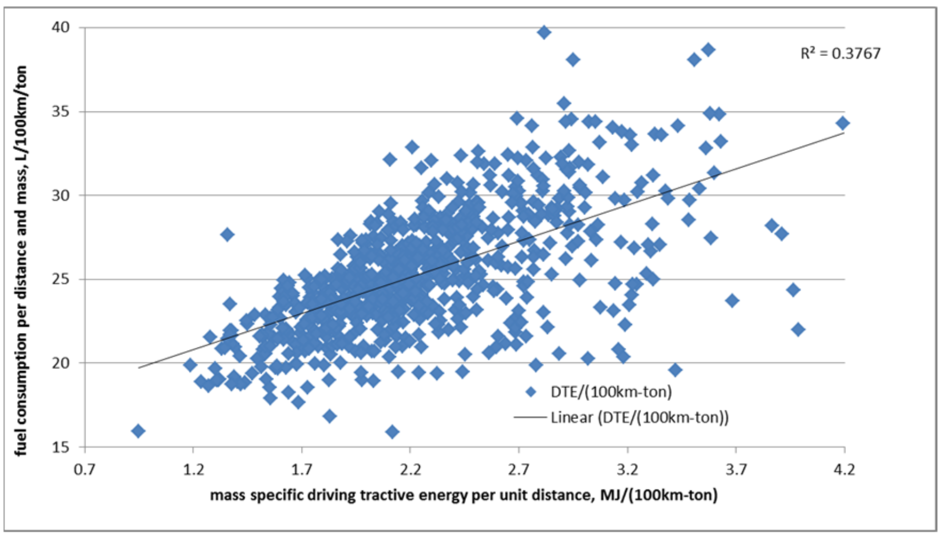


Figure 67: Relationship between the mass specific fuel consumption per unit distance and the MSDTE per unit distance, plotted (a) as a function of the mass and (b) showing the overall correlation between the two variables, for the P&D application.

Although the magnitude of the fuel savings using the tractive energy approach does not match that from the synthetic drive cycle analysis for the P&D cases, the trend predicted for the fuel savings is still consistent using the two methods. A relatively large error in the relative fuel savings is possible with the P&D data using the tractive energy approach since the mass and distance effects are not well correlated on a per trip basis. For the LH application, however, it is believed that the relative fuel savings (1.33%) calculated using the MSDTE/100km is accurate at least to the extent that the mass and distance effects are correlated to the tractive energy. If we assume that the R^2 = 0.741 value shown in Figure 66 (b) allows up to 26% uncertainty in the average fuel consumption per unit distance and mass from the average tractive energy per unit distance and mass, this indicates that the actual fuel savings for the LH application is very likely in the range of 0.9-1.7%.

It is noted that if a single value of average mass were used in the calculation for the LH application, as opposed to considering the mass difference between the LPM enabled and LPM disabled evaluations, the calculation indicates an *increase* in fuel consumption by 2.3% with LPM enabled. The average mass was approximately 3.7% higher during the measurements with the LPM enabled, which would result in an inaccurate conclusion if they had been assumed to be the same. This result shows that even relatively small variations in mass can result in errors in the fuel economy evaluation, which highlights the critical importance of the mass data for the fuel economy benefit analysis.

Fuel Saving Potential of V2X Technology

Benefits of V2V/V2I with the proposed system

In stop-and-go driving, a significant amount of fuel is consumed due to braking and subsequent accelerations, and up to 30% of fuel consumption in off-freeway travel can be attributed to the considerable speed variations that take place in heavy traffic or with frequent traffic signals. The energy required to accelerate from a stop to normal highway speeds for heavy duty trucks is significant: a class 8 tractor-trailer loaded to 36,350 kg (80,000 lbs.) and traveling at 20 m/s (~45 mph) has a kinetic energy of nearly 7.3 MJ. Assuming an average engine efficiency of 35% and a lower heating value for diesel of about 42.7 MJ/kg, the fuel required during each acceleration to this speed (to provide just the kinetic energy) is therefore calculated to be approximately 0.5 kg, which is slightly less than 0.6L of diesel. It is evident that minimizing the amount of braking done by vehicles can provide dramatic fuel savings, particularly for heavy-duty trucks.

Impact of V2I

As a vehicle approaches a lighted intersection, advanced knowledge of signal phase and timing (SPaT) data allows the determination of a speed profile that can reduce or fully eliminate the need for braking. Figure 68 (a) shows an approach to a signal at a nearly constant vehicle speed, requiring active braking near the intersection if the signal changes to red. For the same approach to the intersection (Figure 68 (b)), if the SPaT data is known far enough in advance (D_{v2x}), the vehicle can anticipate the stop and begin coasting well in advance (D_{slow}) of arrival at the intersection. The kinetic energy, which would be otherwise lost through braking, is used to carry the vehicle forward. The active driver assistance system can defuel the engine during the entire coasting period, providing for the fuel savings. Depending on the duration of the red light cycle, when the data is actually received (D_{v2x}), and the point during the signal's timing cycle when the vehicle would normally arrive at the intersection, braking may or may not be required. However, if D_{v2x} is far enough in advance and there is no traffic, it is possible for the vehicle to coast to a stop or arrive at the intersection only after the signal changes to green. Using a simple trajectory model that accounts for the vehicle mass, aerodynamic drag characteristics, the tire rolling resistance, the roadway grade profile and initial vehicle speed, the necessary distance D_{slow} needed to decelerate before arrival at the light can be calculated based on the SPaT data. If $D_{v2x} > D_{slow}$, then a fully optimized approach speed profile can be followed, otherwise it will be necessary to brake during at least some portion of the distance to the light. Even in this case, the advanced warning for the traffic signal data permits some reduction in fuel consumption relative to the case without any SPaT data. An additional benefit is the lower brake pad wear.

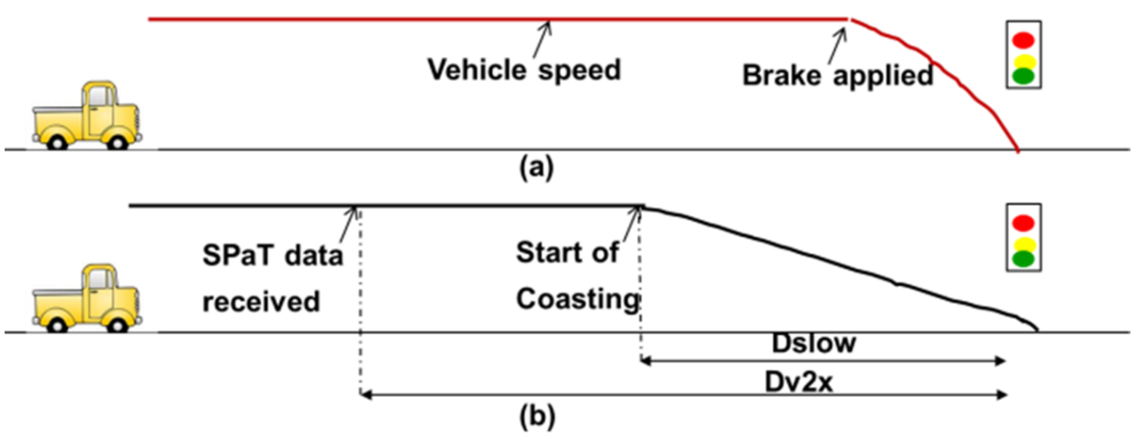


Figure 68: (a) Normal approach to an intersection, without prior knowledge of SPaT data. (b) Approach when SPaT data is received in advance of the intersection

We assume that it is equally likely to arrive at any given time during the signal's overall cycle (one cycle corresponds to the time from one red-to-green signal change to the next red-to-green change). An "approach scenario" is defined by any combination of values for (i) the initial vehicle approach speed v_0, (ii) the distance D_{v2x}, and (iii) the phase of the cycle. The fuel savings for each approach scenario are calculated for each parameter set using a truck model developed in Autonomie vehicle performance software, developed by Argonne National Laboratory [17]. A discrete combination of values of the scenario parameters is utilized. We assume that without SPaT information, the vehicle begins braking when the signal changes from green to yellow in each scenario. Several hundred cases are used for the analysis. After all of these runs are complete, the individual cases are combined using the distribution data to obtain an average value of the fuel savings that is expected during approaches to an intersection. Using the analysis results corresponding to each approach scenario described above, the expected fuel savings from the system using V2I can be quantified for different assumptions of SPaT data availability (technology penetration). Additionally, studies of the fuel savings that are possible when greater transmission distances are used (for example, if a DSRC transmitter is located 1-2 km before each traffic signal instead of directly at the intersection) will help in prioritizing additional ITS deployments.

Impact of V2V

V2V technology holds the potential to provide comprehensive data on localized traffic speeds with a granularity that is not otherwise available. This information can be used to forecast and optimize the speed profile for improved efficiency in much the same manner as the SPaT data discussed previously when vehicles are slowed or stopped along the route of travel. However, since vehicle data can cover all locations on the highway, its utility for speed profile optimization may be expected to be more generally applicable and have greater impacts, at least when data is available from a large population of vehicles and for highway segments where traffic signals are not present or are relatively sparse. Prior research [15] has shown that a look-ahead time horizon of 60 seconds used for speed profile optimization could yield improvements in fuel economy of up to 35% for passenger vehicles, and time horizons as low as 20s resulted in fuel economy gains exceeding 10%. Since momentum is more important for heavy-duty vehicles, it is expected that a longer look-ahead time will be required to achieve the same percent improvements, but V2V will certainly provide fuel savings on top of those that can be achieved with V2I data.

V2V data can be complementary to V2I SPaT data. Using SPaT data, a vehicle's speed can be adjusted so that it arrives at the intersection with a positive speed when the light turns green. However, the presence of stopped vehicles would still force the vehicle to brake upon arrival, which could negate much or all of the fuel savings. The extensive availability of V2V data in the future will allow each vehicle to provide not only data on its instantaneous speed and location, but also for a projected (future) speed profile that can be updated to reflect real-time traffic conditions as any new traffic information becomes available. V2V communication of predicted speed profiles will enable highly coordinated and optimized speed control among vehicles, which can produce fuel efficiency and mobility benefits not only at the individual vehicle level but for all vehicles operating in the traffic network. At a sufficient level of maturity and penetration of V2V technology, traffic speed and traffic density at every location on the highway network could be known to a degree for which precise travel time estimates would also be possible.

Initial Simulation Results

An Autonomie fuel economy model was developed to estimate the benefits of using V2I SPaT data in a HD truck configuration. Autonomie is an open-architecture powertrain and vehicle systems simulation tool developed at Argonne National Laboratory [17]. A conventional powertrain class 8 tractor-trailer model was adapted from a model included in Autonomie, and the modified model has been tuned to correspond to vehicles tested by ORNL [18]. A Heavy Truck Duty Cycle (HTDC) database is available to extract real-world drive cycle measurements covering a broad range of operating conditions [19]. For the purposes of this evaluation, we searched ORNL’s HTDC database for a moderately loaded truck decelerating during an approach to an intersection. The segment chosen (Figure 69) corresponds to a monotonically decelerating vehicle with a total mass of approximately 30,000 kg. It consists of a 48-second deceleration from approximately 90 km/hr to a complete stop, representing an average rate of deceleration of 0.52 m/s^2. The minimum and maximum decelerations over the segment are 0.117 and 1.439 m/s^2, respectively. The Autonomie truck model was configured to correspond to the same loading condition and truck parameters that this drive segment represents. Since performing an Autonomie simulation requires a drive cycle beginning and ending at zero speed, an acceleration from zero to 90 km/hr was also selected from the same day of travel to serve as the start of the drive cycle, and a constant 90 km/hr speed segment was included to define the reference drive cycle. The modeled consumption during the acceleration and constant speed segments of the drive cycle are identical in all of the simulations. As we only consider changes in the fuel consumption, the contribution from this portion of the drive cycle is subtracted and does not affect the final results.

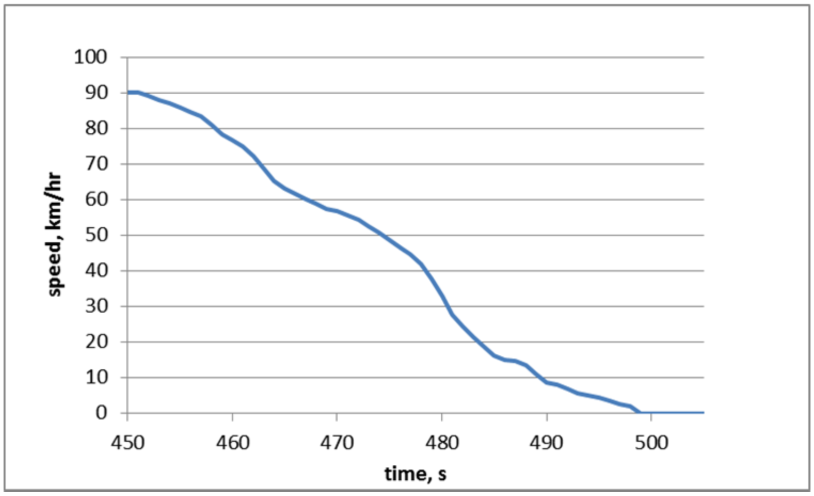
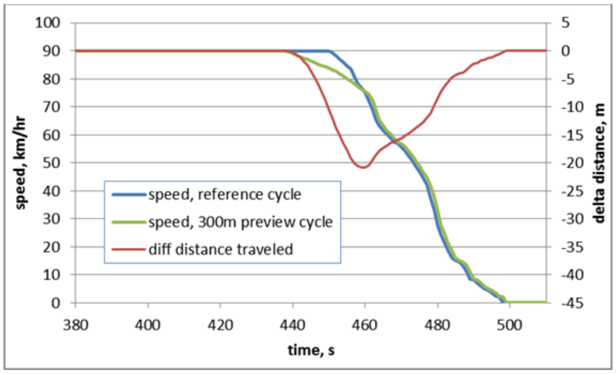
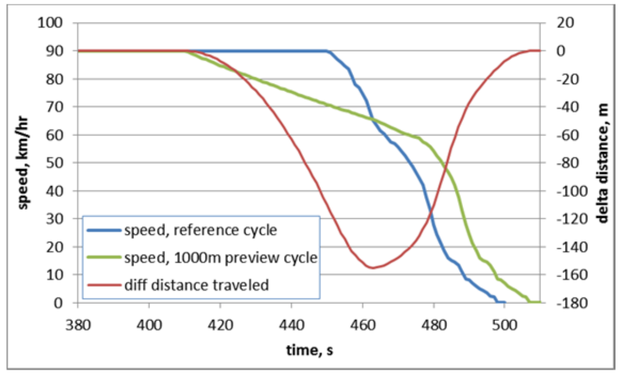


Figure 69: Deceleration segment used for an Autonomie analysis of V2I benefits for a class 8 tractor-trailer

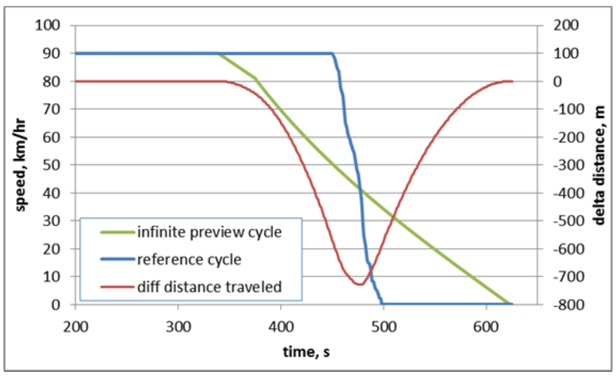
In order to evaluate the fuel savings that can be achieved, the reference drive cycle was modified to simulate response to SPaT information received at different points during an approach to the intersection. It is assumed that the vehicle will be required to make a full stop at the intersection. When the vehicle receives information regarding an impending red light, it begins to coast instead of maintaining the cruising speed of 90 km/hr, resulting in fuel saving. The drive cycle modifications correspond to advance notice being received with a distance horizon, (also referred to as the preview distance), of 300m, 1000m and 3500m. The latter case effectively corresponds to an infinite horizon. If complete SPaT data were available with a sufficient horizon, it is possible for the vehicle to arrive at the traffic light while still moving shortly after the signal changes to green, traffic permitting. This is expected to provide very similar results in terms of fuel savings as the modeled case in which the vehicle is allowed to coast to a full stop.

The modified approach-to-intersection drive segments are shown as a function of time for the three cases in Figure 70 (a)-(c). The reference drive cycle is shown in blue for comparison in each case, and the difference between the distance traveled for each cycle and in the reference cycle is presented as a function of time in red. The case with 300m preview results in very little delay relative to the reference case, and the position of the vehicle relative to the trajectory in the reference case only lags by up to about 21m. If other vehicles were present and did not receive and react to the SPaT data during the intersection approach, this is the gap that would form between vehicles as a result of the coasting. For the 1000m preview case, the maximum difference in position relative to the reference cycle is over 150m, and the delay in arriving at the intersection is about 10 seconds, while in the infinite preview case, the maximum difference in distance is over 700m and the delay to arrive at the intersection is nearly 150s. Depending on traffic conditions, a significant gap between vehicles could be perceived negatively, although if the light remains red, there is no penalty in travel time due to the modified approach.





(a) (b)



(c)

Figure 70: The speed history compared to the reference speed for (a) the 300m preview case, (b) the 1000m preview, and (c) the infinite preview case. The red curve is the difference in position between the followed trajectory and that corresponding to the reference.

Note that the speed modifications were developed to arrive at the same locations and have similar decelerations at the end of the approach to the intersection, even if there is a time delay in the arrivals caused by the initial coasting periods. Figure 71 shows a comparison of the speeds as a function of the distance traveled as opposed to time, and we see that the final deceleration follows the same path as the reference case when braking is necessary.

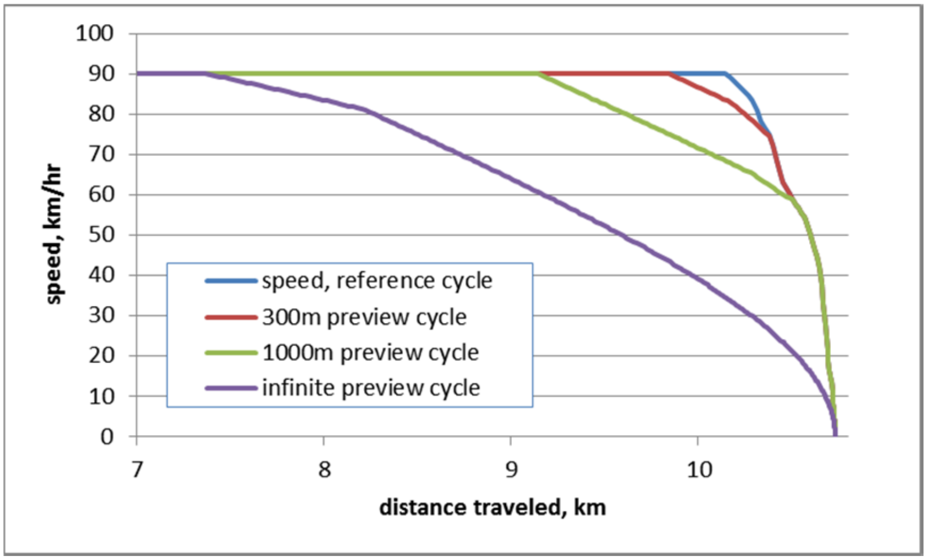


Figure 71: Comparison of the speed history for all four cycles as a function of distance traveled

The results of the fuel savings predicted by Autonomie are presented in Table 24 for the three scenarios in which advanced SPaT information is used to modify the drive cycle. It is noted that the model did not shut off the engine during the decelerations, so even greater fuel savings would be possible with an optimized system employing engine stop-start. The drive cycles modeled are 10.73 km in total length (as noted, all cases were developed to end at the same point when arriving at the intersection), and the fuel consumption for the reference case was 4.41 liters. The initial segments are identical for all three cycles, so the fuel savings for the modified drive cycles corresponds specifically to the difference in decelerations for the approach to the intersection. It is rather impressive that even with a relatively short advance notice of 300m, nearly 0.1L can be saved with each intersection approach. If longer distance horizons for the SPaT data transfer can be provided to vehicles, the fuel savings increase significantly. As noted in earlier discussion, braking from typical highway speeds and the subsequent acceleration of a class 8 vehicle can consume well over 0.5L for each vehicle stop. The “infinite preview” SPaT data scenario allows most of the kinetic energy to do useful work by moving the vehicle forward while coasting. Such benefits will yield very significant fuel savings when V2I data becomes broadly available and is used by trucks to optimize drive cycles for fuel economy.

Table 24: Fuel savings relative to the reference cycle predicted by Autonomie simulations for the three advanced notice SPaT data scenarios

Preview (m)	Predicted Fuel Savings (L)
300	0.09
1000	0.31
3500	0.56

Comments on Successful Use of V2I for Fuel Savings

Despite the significant fuel saving and emission reduction potential, there are several challenges for wide adoption of the proposed technology. In order for the V2I information to be useful for fuel economy improvement in heavy vehicles, the distance at which the SPaT information becomes available plays a critical role (Table 24). Simulations show that an advanced notice distance of greater than 1 km provides good FE-improvement while a distance of greater than 3.5km provides the best FE-improvement. Figure 72 shows initial experimental results from DoT's V2X test-bed at Telegraph road in Southfield, Mi. In this test, the maximum range of V2I was noticed to be around 250 meters. With the planned hardware upgrade of the test-bed, there is a possibility of increasing this range. For additional range increase, the road side transmitters can be located 1-2km before each traffic signal instead of the intersection. Devices that can access SPaT data in real time over internet and correct the information using road side transmitters may provide infinite preview and will result in the maximum FE-improvement possibility.

Similar to the case of V2I communications, one may expect that the distances over which V2V signals are transmitted using DSRC technology may not provide sufficient time horizon to effectively respond to dynamic traffic speeds in a way that provides the greatest fuel economy benefits. DSRC has been selected for use in most ITS applications primarily for the low latency of data transfers, which is necessary for the safety applications that have been the primary focus of ITS research. Since signal transfers with DSRC are possible only over relatively short distances, the benefits for fuel economy applications that function optimally with longer look-ahead time horizons may be reduced. It may be possible to use multi-hop data transmissions [20] to extend the effective range of the transmitted signals, but gaps in traffic could make this approach ineffective, and there are various complications with rebroadcasting non-current data that would need to be resolved and implemented in a common standard. The use of different technologies for V2V data transfers may need to be considered for fuel efficiency optimization and other ITS applications that require time horizons beyond those that DSRC can provide.

Further research is needed to better understand the needs of these applications in terms of the transmission distances that yield optimal performance.

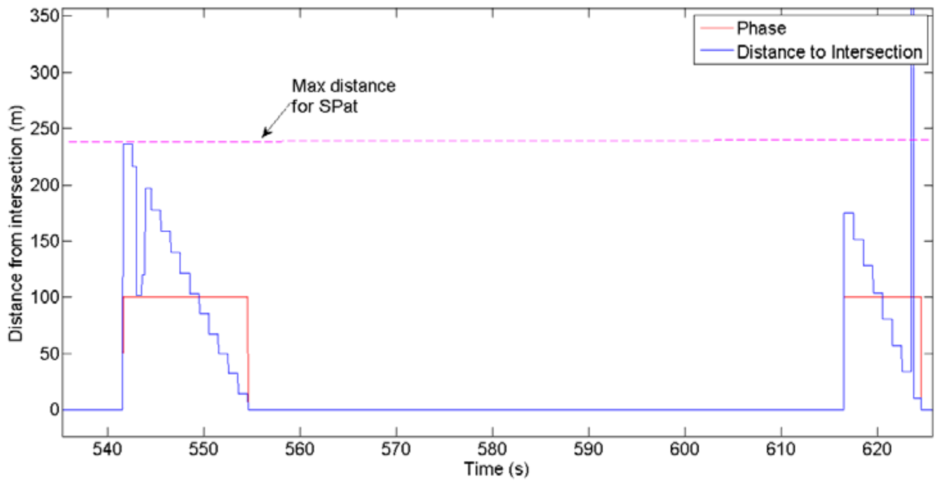


Figure 72: Distance from intersection (blue) and Phase versus travel time. Phase value of 100 indicates green light

Table 25: Project Milestones and Deliverables

Milestone Status Table (for Budget Period III)

ID	Milestone Descriptions	Planned Completion	Actual Completion	Comments
1.1	Kick off meeting with DoE	11/30/2011	11/30/2011	100%
1.2	Project management plan update #1	1/30/2012	1/26/2012	100%
2.1	Voice of customer validation and functional requirements	9/28/2012	9/28/2012	100%
2.2	Identify and prioritize the driving scenarios and driver behaviors that have the most impact on fuel economy based on analysis through existing naturalistic driving data	6/30/2012	7/15/2012	100%
3.1	Completion of the functional specifications of the prototype system	9/30/2012	11/30/2012	100%
3.2	Gen 1 look-ahead fusion engine development	1/15/2013	1/15/2013	100%
3.2.1	Completion of the functional integration of DSRC	1/31/2012	2/27/2012	100%
3.2.2	LAFE hardware design down selection	3/30/2012	3/30/2012	100%
3.2.3	Completion of DSRC integration on the prototype truck	6/30/2012	8/29/2012	100%
3.2.4	Gen 1 LAFE hardware development	1/15/2013	1/15/2013	100%
3.2.5	Gen 1 LAFE software development	1/15/2013	1/15/2013	100%
3.3	Human-machine interface concept development	12/24/2012	11/30/2012	100%
4.1	Perform driving simulator study and down select Human-to-machine	6/28/2013	10/4/2013	100%

	Interface			
4.1.1	Program designed simulator study on driving simulator	4/29/2013	6/13/2013	100%
4.1.2	Completion of human subject testing in the UMTRI driving simulator	5/15/2013	8/27/2013	100%
4.1.3	Driving Simulator experiment report documenting the test, test results and insights relevant to the project	6/28/2013	11/12/2013	100%
4.2	Finalize Human-to-machine Interface Algorithm and Hardware Development	6/28/2013	12/15/2013	100%
4.2.1	Selection of in-vehicle display	4/30/2013	6/28/2013	100%
4.2.2	Finalize the interface between HMI and LAFE sw	5/31/2013	5/31/2013	100%
4.2.3	Programming the display scenarios	6/28/2013	10/4/2013	100%
4.2.4	HMI display: functional and technical document	6/28/2013	11/13/2013	100%
4.1	Perform driving simulator study and down select Human-to-machine Interface	6/28/2013	10/4/2013	100%
4.1.1	Program designed simulator study on driving simulator	4/29/2013	6/13/2013	100%
4.1.2	Completion of human subject testing in the UMTRI driving simulator	5/15/2013	8/27/2013	100%
4.1.3	Driving Simulator experiment report documenting the test, test results and insights relevant to the project	6/28/2013	11/12/2013	100%
4.2	Finalize Human-to-machine Interface Algorithm and Hardware Development	6/28/2013	12/15/2013	100%

4.2.1	Selection of in-vehicle display	4/30/2013	6/28/2013	100%
4.2.2	Finalize the interface between HMI and LAFE sw	5/31/2013	5/31/2013	100%
4.2.3	Programming the display scenarios	6/28/2013	10/4/2013	100%
4.2.4	HMI display: functional and technical document	6/28/2013	11/13/2013	100%
4.3	System Integration and Validation on the Prototype Vehicle	11/29/2013	5/27/2014	100%
4.3.1	Identify the prototype vehicle and obtain required agreements for project use in phase II	4/30/2013	4/22/2013	100%
4.3.2	DAS data dictionary, including signals from the LAFE and other inputs	5/31/2013	5/31/2013	100%
4.3.3	DAS, HMI, LAFE and other equipment integrated onto the prototype vehicle	7/31/2013	12/1/2013	100%
4.3.4	Feedback received from team drivers exposed to the prototype system	9/30/2013	5/1/2014	100%
4.3.5	Summary of the system functionality validation results from the prototype vehicle	11/29/2013	5/27/2014	100%
5.1	Data Acquisition System build 1	7/1/2013	8/15/2013	100%
5.2	Pilot Test Planning	12/15/2013	5/1/2014	100%
5.2.1	Secure commitment from a fleet for Phase III testing	9/30/2013	10/23/2013	100%
5.2.2	Fuel consumption measurement plan for Phase III	4/30/2013	3/30/2014	100%
5.2.3	Prepare test plan and documents for	12/15/2013	12/15/2013	100%

	Phase III IRB submission			
5.3	Pilot Test vehicle preparation (I)	1/15/2014	5/1/2014	100%
6.1	Pilot Test Vehicle Preparation (II)	1/15/2014	6/4/2014	100%
6.2	Pilot test	3/3/2014	7/11/2014	100%
7	Technology Evaluation and final report	3/31/2015	3/31/2015	100%

4.0 PRODUCTS DEVELOPED

a. Publications (list journal name, volume, issue), conference papers, or other public releases of results:

    a. "A Driver Assistance System For Improving Commercial Vehicle Fuel Economy" submitted to Symposium on International Automotive Technology (SIAT), 2013, Pune, India.

    b. "Fuel economy improvement potential of a heavy duty truck using V2x communication" Intelligent Transportation Systems World Congress, September 2014, Detroit, MI, USA.

    c. "Grade adaptation for Improving Commercial Vehicle Fuel Economy – Experimental Results" Intelligent Transportation Systems World Congress, September 2014, Detroit, MI, USA.

    d. "An Intelligent driver assistance system for Improving Commercial Vehicle Fuel Economy" accepted, International Journal of Powertrains.

b. Inventions/Patent Applications, licensing agreements:

    a. Filed invention disclosure titled "Using GPS data and vehicle drive data to develop a location based road load model" (Eaton PDS #12-rVTI-316).

    b. Invention disclosure - "Grade adaptation using Dynamic Programming"

    c. Invention disclosure - " Grade adaptation using Heuristic Energy Formulation"

Subtask 7.3: Cost analysis and Technology benefit

The technology benefit has been discussed in the previous section. This section will focus on the cost analysis. The main components that go into the production Look-ahead system are as follows:

1) eHorizon information provider: This is an embedded hardware platform that provides information on the upcoming road topology as well as the traffic information.
2) Map and traffic data subscription fee: The eHorizon information provider usually installs map software provided by the map suppliers. The map supplier may charge an additional subscription fee for providing data access.
3) Embedded controller to host the software executable: The Look-ahead executable may need an additional controller to host it. This controller can be one of the existing embedded controller on the truck, for example the on-board navigation unit.
4) Sensor cost: The implemented system incorporates a radar for local traffic awareness. If the truck is equipped with advanced safety features, such as Automated Emergency Braking and Forward Collision Warning, the existing radar can be utilized.

We performed a cost sensitivity analysis based on the following cost assumptions. Please note that the final cost to the end user may be different based on the manufacturer as well as other factors such as volume and the value chain.

Cost assumptions: All cost assumptions are for the cost to the end user. We assume that the approximate cost of eHorizon module device may be in the range of $1400-$2000, map and traffic data subscription fee may be from $0 to $400, embedded controller may be $0 (if it can be hosted on an existing ECU) to $400 and the radar cost may be $3000. Based on these assumptions, the following table presents the cost analysis to the end user.

Table 26: System Cost Analysis

	Radar already present		**Radar not present**	
	Minimum Price	**Maximum Price**	**Minimum Price**	**Maximum Price**
Expected price to customer	1400	2800	4400	5800
utilization	120000	120000	120000	120000
MPG	6.25	6.25	6.25	6.25
Fuel consumption	19200	19200	19200	19200
Cost of fuel $	3	3	3	3
Baseline fuel cost	57600	57600	57600	57600
Fuel saving	2	2	2	2
$ Fuel saving	1152	1152	1152	1152
Payback period	1.215278	2.430556	3.819444	5.034722

Table 26 shows the cost analysis for the system. The minimum price corresponds to the case when the single cost of enabling this system comes from the hardware cost of eHorizon module resulting in a payback period of about 1.2 years to the end customer. If the cost of data subscription and additional hardware to host the Look-ahead system are also factored in, the payback period doubles to 2.4 years. Thus, if a radar is already installed on the vehicle, the payback period can range between 1.2 to 2.4 years to the end customer. However, if a radar is not already present on the vehicle and needs to be installed in order, the payback period ranges from 3.8 years to 5 years.

It is noteworthy that the price of a gallon of diesel fuel impacts this calculation significantly. If the price of a gallon of diesel is assumed to be $4 per gallon, the payback period range for the case when radar is already present becomes 1 year to 1.8 year and 2.8 years to 3.8 years for the case when the radar needs to be installed.

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