# Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase One Final Report

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**16. Abstract**


Under the FHWA Exploratory Advanced Research project "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment" this document provides a summary of Phase I results for evaluating the commercial feasibility of Driver Assistive Truck Platooning (DATP).

DATP is a form of Cooperative Adaptive Cruise Control for heavy trucks (two truck platoons). DATP takes advantage of increasing maturity of vehicle-vehicle communications, plus widespread deployment of DSRC-based V2V connectivity expected over the next decade, to improve freight efficiency, fleet efficiency, safety, and highway mobility, plus reduce emissions. Notably, truck fleets can proceed with implementing DATP regardless of the regulatory timeline for DSRC.

Results of Phase I research are provided here. Phase I examined industry perceptions of DATP to provide input to a preliminary business case analysis. Technical investigations addressed system modeling and on track evaluations, aerodynamics modeling, operations research to develop algorithms for platoon formation, initial human-machine interface evaluations, wireless communications examining DSRC aspects specific to tractor-trailer combinations, and traffic modeling to assess traffic flow impacts with various levels of DATP market penetration. Appendices include a DATP Concept of Operations and Requirements document. Phase II plans are also described.


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# *Executive Summary*

The FHWA Exploratory Advanced Research project "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment," led by Auburn University, is performing research and evaluation to assess the commercial viability of truck platooning. Joining Auburn University on the team are partners Peloton Technology, Peterbilt Trucks, Meritor WABCO, and the American Transportation Research Institute (ATRI) (a research organization within the American Trucking Associations Federation). The lead organization within Auburn is the GPS and Vehicle Dynamics Laboratory (GAVLAB).

For the particular form of Cooperative Adaptive Cruise Control (CACC) addressed here, the term "Driver Assistive Truck Platooning" (DATP) has been developed to support stakeholder engagement with the trucking industry. In DATP, two or more trucks are exchanging data, with one or more trucks closely following the leader. The technology basis includes radar (for longitudinal sensing), DSRC-based V2V communications (for low latency exchange of vehicle performance parameters between vehicles), satellite positioning (sufficient to discriminate in-lane communications from out-of-lane communications), actuation (for vehicle longitudinal control), and human-machine interfaces (with distinct modes for leading or following). As a Level 1 Automation system, only longitudinal control is automated; the driver remains fully responsible for steering and has the ability to override system brake or throttle commands at any time.

The intent of this research is to investigate business factors of DATP operations and the extent of potential reductions in fuel consumption, as well as safety, system robustness, and transportation impacts. This document provides a summary of Phase I results. For this project, the going-in hypothesis is that "*DATP technology is near market-ready for industrial use and will provide value in specific roadway and operating conditions for heavy truck fleet operations.*" This research addresses the necessary technical work, evaluation, and industry engagement to identify the key questions that must be answered prior to market introduction of heavy truck DATP, and to answer those questions. These questions must address industry needs as well as the needs of other highway travelers relating to traffic flow and safety.

DATP builds on Adaptive Cruise Control, which has been available to the trucking industry for several years (approximately 100,000 ACC-equipped Class 8 trucks are on the road now). DATP has significant positive safety and fuel savings potential for heavy truck operations beyond what ACC can deliver alone. DATP also extends the functionality of forward collision mitigation systems (CMS), and may provide fleet users with extra incentives for CMS adoption due to prospective safety and fuel savings. The fuel savings offered by DATP are additive with fuel gains achieved with Predicitive Powertrain systems using 3-D mapping technology.

Long haul trucking alone represents more than 10% of US oil use, with fuel representing 41% of fleet operating expenses. Regarding fuel economy, previous testing has shown that due to aerodynamic drafting effects, DATP has the potential to significantly reduce fuel use: on the order of 4% for the lead truck and 10% for the following truck. In terms of safety, the radar-based system provides an additional level of situational awareness to the driver whether DATP is activated or not. The most common highway accident for heavy trucks is frontal collisions. A DATP system enable the following truck(s) to react more quickly to changes in speed by the lead truck. This provides a faster reaction to upcoming hazards by the following truck than is available from current systems.

Notably, truck fleets can proceed with implementing DATP near-term regardless of the regulatory timeline for DSRC.

Phase I work included development of a DATP Concept of Operations and System Requirements document and a DATP Requirements document. The ConOps section addresses operational needs, user-oriented operations, the system approach, the operational environment, the support environment, and operational scenarios. The Systems Requirements section provides high-level system requirements and is organized into the major sections of Driver Role, On-Board System, and Inter-vehicle Communications. This document is attached here as an appendix.

Phase I of this research found:

- "Truckload" and line-haul "less-than-truckload" fleet operations appear to be a likely fit for early adoption of DATP.
- A trucking industry survey conducted by the team included these findings (which should be considered preliminary since respondents had no experience with DATP at this early stage):
    - 54% of carriers and drivers had an average trip length of less than 500 miles, and 46% were over 500 miles in average trip lengths. Longer trip lengths in DATP operations are more likely to generate greater return on investment.
    - 54% of fleet managers indicated that the DATP systems would have a "very positive," "somewhat positive," or no impact on driver retention. 39% of fleet manager respondents feel that drivers are very likely, likely, or moderately likely to use a DATP system. Owner-operator response for driver retention or usage was more towards the negative end of this scale, however.
    - Owner-operators expected a mean DATP payback period of 10 months, while fleet respondents had a mean expectation of 18 months.
- Typical automotive radar shows good tracking ability at headways expected in DATP operations.
- In aerodynamics simulations, the follower vehicle appears to see large amounts of drag reduction, even distances greater than 100 feet. At closer distances these savings are beneficially compounded by lead vehicle drag reduction. The inter-vehicle distances required for leader fuel savings do not appear to be below the margin of safety for the DATP system to be operated.
- Using data of actual truck movements on a section of highway, platoon formation modeling results were promising. Results showed platoon formation of 30-45% in one dataset, with those trucks remaining platooned between 55-75% of the 300-mile road segment.
- Traffic modeling results showed that DATP caused no delays compared to existing conditions. Gaining significant benefits in traffic flow start to appear at truck market penetrations of over 60% with headways lower than 1.25 seconds (approximately 100 feet at 60 mph); DATP headways are expected to be significantly less than this.

During 2015, Phase II work will focus on:

a. System testing: equipping the Peterbilt tractors with the Peloton DATP system plus data acquisition, followed by performance testing at the test track in the areas of wireless communications, vehicle control, positioning, driver comfort, and safety. Additionally, the team will acquire suitable trailers for testing. On-road testing for fuel economy evaluations will be planned, arranged, and conducted.
b. Human factors: providing driver training, assessing driver reactions to operating the system at several points during testing (both on-track and on-road). Interviews will be conducted post-training and after 1-year to understand the impact from both training and hands-on experience towards acceptance, concerns, and potential pros.
c. Wireless communications: on-track testing will seek to stress the DSRC system, which will be evaluated for packet loss, message delay, channel congestion, and other performance indices.

Algorithms and protocols will be designed that improve scalability of DSRC. The team will evaluate an adaptive strategy that allows the DSRC subsystem to prioritize important safety-related messages differently during distinct driving modes.

d. Aerodynamics modeling: developing models with greater detail to support more in-depth evaluations. This will include platoons of more than two vehicles. These models will be integrated with vehicle models to provide a comprehensive evaluation tool for DATP expected to be useful to system developers.
e. Platoon formation: Future modeling with regard to assessing platoon formation will include extending the analysis of the ATRI-provided truck data for additional highway corridors, such as urban corridors, as well as incorporating differences in fuel economy benefits depending on platoon position.
f. Traffic impacts evaluation: modeling different times of day, platoons of more than two vehicles, other highway types, and truck lane restrictions; to include varying truck percentages and modeling three- truck platoons. While the model implementation so far has been focused on freeways, an investigation on a rural arterial that is a major trucking route that is less controlled and includes traffic signals will be done. Finally, it is important to evaluate how traffic overall will operate in entry/exit situations.

Driver Assistive Truck Platooning, if shown to be commercially viable, would lead to new levels of freight/fleet efficiency and improved mobility for all highway travelers, while substantially reducing trucking-based emissions and enhancing the V2X communications environment. Overall project results will constitute an important step towards realizing this potential.

# I. Introduction

The Phase I report has been prepared for the FHWA Exploratory Advanced Research project "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment."

For the particular form of CACC implemented here, the term "Driver Assistive Truck Platooning" (DATP) has been developed to support stakeholder engagement with the trucking industry. DATP builds on Adaptive Cruise Control, which has been available to the trucking industry for several years (approximately 100,000 ACC-equipped Class 8 trucks are on the road now). DATP has significant positive safety improvements, emission reduction, and fuel savings potential for heavy truck operations. The intent of this research is to investigate the extent of potential reductions in fuel cost based on realistic DATP operations, as well as safety and other impacts.

In DATP, two or more trucks are exchanging data, with one or more trucks closely following the leader. The technology basis includes radar (for longitudinal sensing), V2V communications (for low latency exchange of vehicle performance parameters between vehicles), satellite positioning (sufficient to discriminate in-lane communications from out-of-lane communications), actuation (for vehicle longitudinal control), and human-machine interfaces (with distinct modes for leading or following).

In terms of safety, the radar-based system provides an additional level of situational awareness to the driver whether DATP is activated or not. The most common highway accident for heavy trucks is frontal collisions. A DATP system can actively mitigate these types of accidents without relying solely on driver reaction time. This provides faster reaction to upcoming hazards by the following truck than is available from current systems.

DATP builds on Adaptive Cruise Control, which has been available to the trucking industry for several years (approximately 100,000 ACC-equipped Class 8 trucks are on the road now). DATP has significant positive safety and fuel savings potential for heavy truck operations beyond what ACC can deliver alone. DATP also extends the functionality of forward collision mitigation systems (CMS), and may provide fleet users with extra incentive for CMS adoption due to DATP-generated safety and fuel savings.

DATP takes advantage of increasing maturity of vehicle-vehicle communications, plus widespread deployment of DSRC-based V2V connectivity expected over the next decade, to improve freight efficiency, fleet efficiency, safety, and highway mobility, plus reduce emissions. Notably, truck fleets can proceed with implementing DATP regardless of the regulatory timeline for DSRC. Long haul trucking alone represents more than 10% of US oil use, with fuel representing 41% of fleet operating expenses. Testing in past FHWA EAR research and by project partner Peloton has shown that, due to aerodynamic drafting effects, DATP has the potential to significantly reduce fuel use. Peloton's on-road tests have shown significant improvements on the order of 4% for the lead truck and 10% for the following truck, when traveling at 100 kph at 11m spacing (Roeth, 2013; Browand, 2004).

Our hypothesis is that "*DATP technology is near market-ready for industrial use and will provide value in specific roadway and operating conditions for heavy truck fleet operations.*" The objective of this research is to perform the necessary technical work, evaluation, and industry engagement to identify the key questions that must be answered prior to market introduction of heavy truck DATP, and to answer those questions. These questions must address industry needs as well as the needs of other highway travelers relating to traffic flow and safety.

Auburn University is working in conjunction with the American Transportation Research Institute (ATRI), Peloton Technology, Peterbilt Trucks, and Meritor WABCO in performing this research.

This research could lead to new levels of freight/fleet efficiency and improved mobility for all highway travelers, while substantially reducing trucking-based emissions.

## a. Partners

### i. American Transportation Research Institute (ATRI)

ATRI maintains one of the world's largest databases of real-time and near-real time truck GPS data. The Freight Performance Measures (FPM) program is partially sponsored by the FHWA to provide average travel times, speeds and reliability measures on the Interstate system. Beyond these activities, ATRI has successfully developed processes and algorithms for monitoring and managing truck travel throughout North America. The FPM database includes more than 500,000 large trucks that operate throughout North America. The data has been used by MPOs, State DOTs and the U.S. DOT to support multiple freight transportation objectives. ATRI will apply this FPM data to the project.

### ii. Peloton Technology

Peloton is a vehicle-safety technology company that combines vehicle-to-vehicle (V2V) communications, active safety systems and driver alertness tools to improve the collision avoidance capabilities and fuel efficiency of Class 8 trucks. The company's DATP system builds on adaptive cruise control and forward collision mitigation systems already in use in the long-haul trucking industry. It connects trucks to other vehicles, infrastructure and the cloud. Based in Mountain View, California, Peloton has demonstrated its DATP system on Class 8 trucks in states including Utah, Nevada and Michigan, in conjunction with state DOTs and research institutions.

### iii. Peterbilt Trucks

Peterbilt Trucks is a major manufacturer of heavy trucks and performs advanced engineering, bringing this perspective to the project as well as contributing trucks to the research.

### iv. Meritor WABCO

Meritor WABCO is a 50/50 Joint Venture between Meritor and WABCO, established in 1990. The company, a leader in the integration of safety and efficiency technology for the commercial vehicle industry in North America, is a major supplier of Anti-Lock Braking, Electronic Stability Control, and Collision Mitigation systems for Class 8 tractors. Specifically, M-W is providing its OnGuard™ Collision Mitigation System (CMS) to form part of the technology foundation for the platooning system. M-W also provides in-depth expertise and experience based on its role as a commercial systems supplier.

### v. Auburn University

The primary groups within Auburn on the project are the GPS and Vehicle Dynamics Laboratory (GAVLAB); the Wireless Engineering Research and Education Center within the Computer Sciences and Software Engineering Department (CSSE); the Occupational Safety and Ergonomics Laboratory (OSE); the Industrial and Systems Engineering Department (ISE-MW); and the Numerical System Simulation & Aerodynamic Modeling Research Work Group (ARG), and the Highway Research Center within the Civil Engineering Department (CE). The National Center for Asphalt Technology test track provides a vital facility for testing.

#### 1. GPS and Vehicle Dynamics Laboratory (GAVLAB)

The GAVLAB is composed of mechanical and electrical engineers, and it focuses on the control and navigation of vehicles using GPS in conjunction with other sensors, such as Internal Navigation System (INS) sensors. The GAVLAB is undertaking several tasks, including developing simulations of the sensory technology using TruckSim, writing algorithms for sensor fusion for robust positioning, estimation of truck properties including mass and engine torque, and live implementation of the system. The GAVLAB is also supported by Bishop Consulting, which provides project management, system engineering and stakeholder liaison.

**2. Wireless Engineering Research and Education Center (CSSE)**

The main objectives of the CSSE group are design, implementation, and evaluation of vehicle-vehicle (V2V) communication for CACC, in which critical requirements for wireless networks that support for automated truck platooning are satisfied by providing high reliability in the transmission of control information, security against various forms of attacks and high data rates for rapid delivery of large amount of control and driver feedback data.

**3. Occupational Safety and Ergonomics Lab (OSE)**

Auburn's Occupational Safety and Ergonomics Laboratory (OSE) is responsible for the human-machine interface (HMI) as well as guidance on safety related issues. These contributions are being provided through collaboration with ATRI, online resources, pre-existing knowledge, and hands-on experience with trucks installed with platooning technology.

**4. Industrial Systems and Engineering Department (ISE)**

The ISE-MW group is responsible for analyzing current trucking traffic to identify critical freight corridors in which platooning operations are likely to be viable as a result of CACC. This analysis addresses the feasibility of platoon formation in real world settings, the determination of estimated expected platoon sizes, impacts to delivery schedules, and waiting times for trucks to join a platoon.

**5. Numerical System Simulation & Aerodynamic Modeling Research Work Group (ARG)**

ARG is responsible for developing an aerodynamic model of the two truck leader-follower configuration. The primary purpose of the model is to determine the decrease in drag coefficient that is achieved through platooning and develop a correlation between leader-follower separation distance and the absolute drag reduction. The drag-separation model will ultimately will be used to estimate vehicle fuel savings. Graduate student Andrew Watts is currently heading ARG's portion of the project.

**6. Civil Engineering—Highway Research Center (HRC)**

The Highway Research Center (HRC) is composed of Civil Engineers in the specialty of Transportation, and focuses on highway operations such as planning and safety. The HRC is working on traffic simulation using VISSIM, and statistical analysis of data obtained from these simulations. Dr. Rod Turochy and graduate student Mikhail Gordon are working on the project for the HRC.

**7. National Center for Asphalt Technology (NCAT)**

NCAT was created in 1986 through an agreement between the National Asphalt Pavement Association (NAPA) Research and Education Foundation and Auburn University. NCAT is a major scientific force in pavement research. The testing program uses a two mile oval track built to interstate standards. Individual 200 foot sections of the track have asphalt "recipes" unique to testing clients (State DOTs) from the eastern USA. The pavement is stressed by a fleet of five heavily loaded tractor-triple-trailers running 3400 miles per day. This trucking operation has served as a platform for a wide range of truck-based vehicle technology research and continues in this role for this project.

## b. Research Objectives

"CACC technology is near market-ready for industrial use and will provide value in specific roadway and operating conditions for heavy truck fleet operations." – this is our hypothesis. The objective of this research is to perform the necessary technical work, evaluation, and industry engagement to identify the key questions that must be answered prior to market introduction of heavy truck CACC, and to answer those questions. These questions must address industry needs as well as the needs of other highway travelers relating to traffic flow and safety. This work, if successful, will lead to new levels of freight/fleet efficiency and improved mobility for all highway travelers, while substantially reducing trucking-based emissions.

Specifically, research objectives are:

- Define a commercially viable Level 1 platooning system (DATP)
    - technically viable
    - operationally viable for commercial fleet operations
- Assess DATP by implementing a prototype system that meets the user needs and can have maximum positive impact on freight efficiency and mobility.
- Report research results to industry

## c. Project Structure

Phase I was structured across several major activities, which are briefly described here. Engagement with trucking industry stakeholders is included throughout the process.

a. Develop Concept of Operations
b. Instrument NCAT Trucks to Perform Sensor/RF Level Assessments
c. Define Requirements
d. Examine Business Case for Near-Term CACC Trucking Operations
e. Perform Preliminary Evaluation of Impacts

# *I. DATP Concept*

## a. Description of DATP

Cooperative Adaptive Cruise Control (CACC) builds on Adaptive Cruise Control (ACC). Automated control of throttle and brakes is not new to the truck industry; ACC was first introduced in 2008 and approximately 100,000 trucks operate with ACC today, almost all of them Class 8 vehicles. DATP also extends the functionality of forward collision mitigation systems (CMS), and may provide fleet users with extra incentive for CMS adoption due to DATP-generated safety and fuel savings.

In a DATP system, two trucks are exchanging data, with one truck closely following the leader. The technology basis is radar (for longitudinal sensing), DSRC IEEE802.11p V2V communications (for exchanging vehicle performance parameters between vehicles), positioning (sufficient to discriminate in-lane communications from out-of-lane communications), actuation (for vehicle longitudinal control), and human-machine interfaces (with distinct modes for leading or following).

Using V2V communications, the two trucks can "electronically couple" such that any initiation of braking by the lead truck can instantaneously be initiated by following trucks. This enables inter-vehicle spacing to be greatly reduced, which also improves aerodynamics and reduces fuel use. Testing of a 2-truck platoon has shown up to a 10% fuel reduction in the following truck and 4% fuel reduction in the lead truck (due to reduced turbulence in the rear).[1] These are very compelling numbers for the commercial trucking industry.

The lead truck is driven in normal ACC mode or manually. For the rear truck driver, longitudinal control is automated and driver responsibility for steering is retained. DATP is therefore a Level 1 automation system. The driver has the ability to override brake or throttle commands from the system at all times.

It is envisioned that wide-area communications allow vehicles to identify and coordinate linking opportunities with other vehicles, both within a fleet or ad-hoc.

In terms of roadway types, DATP is intended to operate on typical interstate highways primarily, as well as other well-structured high-speed road environments.

The most common highway accident for heavy trucks is frontal collisions. A DATP system can actively prevent these types of accidents without relying on driver reaction time. This provides faster reaction to upcoming hazards *by both trucks* than is available from current systems. This is due to the combination of ACC limiting accidents for the front truck and CACC limiting accidents between the two trucks platooning.

In essence, DATP combines developments in collision avoidance technology, advanced control algorithms, and real-time communications (DSRC V2V) to enable the trucking industry to take an incremental step towards vehicle automation in a manner that is economically attractive.

## b. DATP Industry Context

Recent research shows that traffic congestion is a top five issue for the trucking industry, and with the per-hour cost to operate a truck now at $68.50 any initiative that minimizes time delays and congestion-related impacts will likely provide a very solid ROI to industry stakeholders and strengthen the economy. That said, joint research by FMCSA and ATRI conducted in 2008 indicates that the trucking industry's requirements for technology investment include short payback periods, direct net ROIs and minimization of data privacy concerns. Fortunately, the private sector suppliers to the trucking and transportation industries are cognizant of these requirements. Technology adoption rates are now at an all-time high, with nearly 80% of large trucks now using telematics devices.

Given these factors, the proposed research takes advantage of increasing maturity of vehicle-vehicle communications, plus widespread deployment of DSRC-based V2V/V2I connectivity expected over the next decade, to improve freight efficiency, fleet efficiency, safety, and highway mobility, plus reduce emissions. Long haul trucking alone represents more than 10% of US oil use, with fuel representing 41% of fleet operating expenses. DATP has the potential to provide the means for US fleets to save more than 1.25 billion gallons of diesel annually, equivalent to taking millions of cars off the road and reducing carbon output by more than 12 million tons. Further, equipping trucks for DATP would accelerate market penetration of DSRC-equipped vehicles generally, enriching the V2X communications environment, while providing individual benefits to truck fleets making the investments.

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[1] M. Roeth, "CR England Peloton Technology Platooning Test Nov 2013," North American Council for Freight Efficiency, 2013.

Commercial Vehicles have particular attributes that make them attractive for early adoption of automated driving technology, including:

a. More compelling business case with respect to fuel economy
b. Ability to leverage an already integrated and sophisticated freight logistic infrastructure
c. Trained and regulated driver base
d. Providing a technology that might help reduce the anticipated driver shortage
e. Sophisticated service functions at fleets
f. Quick purchasing cycles at fleets (relative to passenger car) allows shorter time to critical mass of adoption

FHWA's Office of Freight Management research documents a relatively untenable freight distribution scenario: freight tonnage will more than double in a twenty-year period, at the same time that infrastructure capacity increases only 3-4%. Strategies for addressing this conundrum are limited: move freight to other modes; move freight to other roadways or shift travel time periods. Research sponsored by TRB's National Cooperative Freight Research Program confirms that these solutions will have limited impact. A more likely approach will be to utilize technology to increase infrastructure capacity beyond the addition of concrete and asphalt. Hence, this research has the potential to move DATP from a futuristic concept to a realistic tool available to transportation managers.

Within the private sector, multi-fleet cooperatives are forming to share customers, shipments and data. It is a natural extension for these cooperatives to start "platooning" trucks and trailers that share similar routing and dispatching environments. While the complexity of fleet types, business models and vehicle configurations are myriad in the trucking industry, the Auburn research team is best positioned to analyze and recommend those scenarios where DATP has the greatest potential – particularly in "regular-route" environments.

## c. Key Questions Going In

A DATP trucking operation, while relatively straightforward technically, constitutes a major step for fleet operators: depending on data from another vehicle for the safety of "my" vehicle. A wide range of questions arise, such as:

- How can my driver find another equipped vehicle? How do I know the other vehicle and the information it is broadcasting are trustworthy?
- How will the following driver retain situational awareness? How does the job of the lead driver change?
- What factors are important to driver understanding and acceptance of the system? What is the best way to introduce drivers to this system?
- How does the system react to passenger car cut-ins and other real-world anomalies?
- How can the system adapt to changes in load?
- How does surrounding traffic interact with the linked trucks?
- What fuel savings are achievable in the real world with real traffic?
- What operating strategies are best suited to use of DATP?
- How do the most promising operating strategies affect traffic flow, particularly in dense freight corridors?
- What are system limitations in terms of the road environment, i.e. curves, urban areas, freeway-freeway interchanges, etc., as well as weather?
- How practical and efficient is the process of finding linking partners on the road?
- What is the effect of CACC on safety performance? Will the system introduce new safety risks, or be limited due to safety factors?

- How will the system adapt to varying braking capability, engine power, and load?
- What technological and institutional enablers are necessary to allow DATP to be commercially established in North America?
- What is the return on investment (ROI) for fleets equipping vehicles with DATP?

## *II. DATP Concept of Operations and Requirements*

The DATP Concept of Operations and System Requirements document consists of two major sections. The ConOps section consists of the following major sub-sections:

a. Operational Needs
b. User-Oriented Operational Description
c. System Overview
d. Operational Environment
e. Support Environment
f. Operational Scenarios

The Systems Requirements section provides high-level system requirements for DATP. It is organized into the following major sub-sections:

a. Driver Role
    a. General Driver Responsibilities
    b. Lead Driver Responsibilities
    c. Rear Driver Responsibilities
b. On-board System
    a. General
    b. Sensing
    c. Positioning
    d. Situation Awareness
    e. Maneuvering and Control
    f. Detection and Reaction to Faults
    g. Human-Machine Interface
c. Inter-vehicle Communications

The full DATP Concept of Operations and System Requirements document is provided as Appendix A.

# *III. User and Business Case Evaluation*

The trucking industry is a large, complex sector of the U.S. economy, utilizing millions of people and assets to move more the 10 billion tons of freight every year. To effect this large-scale freight distribution, numerous vehicle configurations are used. In addition, much of the trucking industry is heavily invested in back room and onboard technology systems that ensure safe and efficient operations.

The sheer number of trucking companies on file with the U.S. DOT, more than 500,000 in 2013, ensures that competition is stiff and operating margins are low. Between 2011 and 2013, operating margins dropped from an average of 3.8 percent to 3.4 percent. While different industry sectors are more or less profitable, every firm is judicious in its assessment of which technologies will generate the highest and quickest return-on-investment (ROI). Using an FMCSA-sponsored benefit-cost assessment of onboard safety systems as a surrogate for all technology assessments done by industry, technology investments are expected to have a payback in 12 to 18 months. And most importantly ROI calculations must be direct and net to the firm; societal benefits are rarely considered in the investment decision process.

The following DATP section provides guidance on the users, sectors, and business models that are most likely to consider investing in DATP systems. In turn, it does not highlight and rationalize those industry markets that are least likely to consider DATP adoption.

The ATRI industry survey solicited both carrier and driver cost and benefit expectations. In general, the industry has knowledge and understanding regarding standard technology and safety systems. However, the respondents had a limited basis for estimating the full scope of costs and benefits of DATP as described in this report. This creates challenges for the survey process, which should be viewed as an *initial investigation* that will be refined as stakeholders gain increased understanding through project activities. Nevertheless insights can be found from these early results that serve to guide the key question for this research project: what does it take for the trucking industry to embrace DATP?

To conduct the survey, a press release was issued through ATRI which detailed truck platooning research, and contained a link to the survey hosted on ATRI's website. This press release was emailed to the entirety of ATRI's industry contact list comprised of motor carriers, company drivers, owner-operators, state trucking association executives, and the like, representing the various sectors of the trucking industry.

A full summary of the survey results can be found in Appendix C. Highlights from the survey are included in the following sections.

## a. Industry Sectors

The DATP concept is most advantageous when travel speeds are higher, truck trips are longer (i.e., benefits accrue over time/distance), and the likelihood of encountering similar trucks installed with DATP is high. These and several other attributes are used to test DATP consideration by sector.

Industry data derived from surveys and technical reports (e.g. ATA Trucking Trends 2013) indicate that over-the-road operations, with an emphasis on "truckload" (TL) and line-haul "less-than-truckload" (LTL) sectors would experience the highest likelihood of encountering the desired DATP attributes.

*Truckload operations* often have pre-determined routes or corridors between large freight generators (e.g. business parks, manufacturing centers, warehouses, retail establishments). In the ATRI Industry Survey, 75% of the time the truck routing was determined in advance of the trip. Although the survey data shows that a meaningful number of these trips experienced unexpected route changes, the ability to potentially concentrate DATP-installed trucks through advance planning, may increase industry interest, at least by those TL firms that have multiple DATP trucks and dedicated lanes between freight generators.

Furthermore, the largest percentage of TL trip mileage occurs on highways and interstates, which immediately improves the attractiveness of DATP to this sector. In ATRI's Industry Survey, 71% of the TL mileage was generated on limited access interstates and highways.

*Table 1: Trip Mileage Percentages with Respect to Truck Loads*

| | Limited Access, 3+ Lanes | Limited Access, 2 Lanes |
|---|---|---|
| Less—than—truckload | 13% | 70% |
| Truckload | 34% | 46% |
| Specialized, tanker | - | 75% |

Another potential aspect of the TL sector that may favor DATP is that, within any one trip, TL shipments by definition have limited cargo types and destinations. This has the effect of further concentrating TL trucks on major corridors between freight generators.

*Less-than-truckload* operations utilize hub & spoke pick-ups and deliveries in urban areas, but rely heavily on the line-haul trips that connect the LTL consolidation terminals in different urban areas. These LTL line-haul trips often mimic the operations of TL trips, thus making them similar candidates for DATP. That said, there are some differences and complexities that must be considered. Many larger LTL operators utilize contractors and even TL firms for line-haul trips. In these instances, the LTL firm may no longer have direct control (or benefits) associated with DATP usage. In addition, LTL vehicles and driver issues (e.g. driver compensation) may differ from TL. On average LTL vehicles are slightly older than TL, meaning that adoption may be slower since DATP is primarily an OEM-installed component.

LTL drivers are often paid by the hour, and may be unionized. In some instances, LTL line-haul drivers are paid by the mile and, again, may be contracted non-LTL trucks. Ultimately, based on route types and distance, line-haul LTL looks promising, but operational nuances and LTL-specific issues may need to be addressed. As an example of ways that some of these issues can be addressed, discussions with LTL carriers have indicated interest in providing incentives for both internal fleet drivers and contractors to encourage the adoption and effective use of DATP systems.

## b. For-Hire vs Private Fleet Operations

Within any one fleet, there may not be a big difference between for-hire carriers and private fleets. The key attributes and investment considerations will still favor longer trips on higher speed roads among similarly installed vehicles. Private fleets do have different business models that weight costs and benefits differently, but in terms of fuel savings the two business models would likely weigh the DATP investment in similar fashions.

Assuming that competition between fleets lessens the attractiveness of DATP, there may be another meaningful difference between for-hire and private fleets. Both for-hire and private fleets are fiercely competitive, but for-hire fleets would likely view any other for-hire fleet in their sector as a competitor. Private fleets, however, may consider partnering with any of the many thousands of private fleets – though one would assume this is less likely for those that share a competitive product line. However, one team member, presenting the potential fuel savings benefits of DATP to stakeholders, has received indications from some private fleets as to their willingness to consider platooning even with direct competitor fleets.

## c. Commodity Types

There does not appear to be a clear commodity issue that harms or favors DATP consideration, but there are several commodity-related considerations.

Most freight would be equal candidates for DATP consideration. While weight is a consideration in the fuel efficiency equation, most 5-axle trucks are loaded below the Federal 80,000 lb GVW limit for common 5-axle trucks. Nevertheless, the anecdotal information is that heavier commodities would benefit slightly more from DATP than would light commodities (e.g. dry food goods) due to lower MPGs for heavier weight commodities. However, if DATP systems deliver the large fuel savings envisioned, the system will likely drive high adoption by long-haul carriers of the full range of cargo weights and types.

## d. DATP Operating Environments

Technically, DATP could likely be used in almost any operating environment with at least some favorable outcome, although it maybe not enough to outweigh purchase and operating costs. For a variety of safety and operational reasons, certain geographic scenarios may mitigate DATP benefits. These include steep road grade issues, traffic speed, congestion, and merging issues, and infrastructure-based issues such as work zones and road design issues (e.g. tight curves). It is possible that the existing DATP system could be redesigned using more sensors to address these issues, but adding components may change the cost-benefit equation.

But certain other operating environments would clearly favor DATP usage. These may include rural segments of the NHS; long, straight segments of roadway; low-volume roads; limited-access freeways, low-volume multi-lane roadways, ITS-enabled roadways, and high truck density routes. Newly studied "truck-only" lanes could also prove advantageous.

In the ATRI industry survey, approximately 65% of the respondents operated primarily on limited access interstates which would favor DATP operations since it would limit other vehicle interference and they typically include multiple lanes in both directions.

## e. Truck Trip Lengths

The research team has not completed an analysis of minimum trip lengths needed to justify DATP operations. Based on the proposition that the longer a truck is engaged in a truck platoon, the greater the benefit, longer trip lengths would generate greater ROIs. Among the industry survey responses, 54% of carriers and drivers had an average trip length of less than 500 miles, and 46% were over 500 miles in average trip lengths.

Analysis of break-even points with respect to trip lengths will be performed in Phase II.

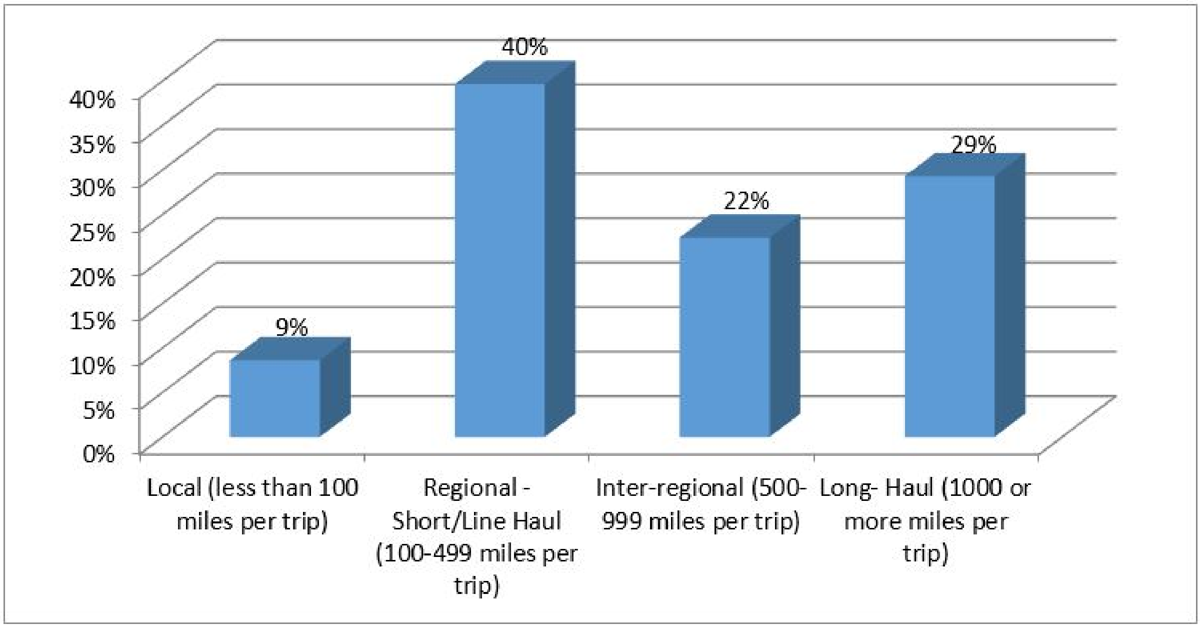


*Figure 1: Type of Haul by Percentage*

**Truck Driver Considerations**. Accommodating truck drivers' needs and expectations will be one of the most important requirements of a successful DATP system. With the growing economy and baby boomer retirements, the truck driver shortage crisis will become more critical. ATRI conducts an annual survey of industry stakeholders and the "truck driver shortage" issue rose to number 2 in the 2014 survey, and it likely will be number 1 in 2015.

So ensuring truck driver support and satisfaction with DATP usage is essential. There are a large range of issues and concerns raised in the ATRI industry survey relating to truck driver usage and truck driver retention. Working backwards on the support continuum, 15% of fleet managers indicated that the DATP systems would have a "very positive" or "somewhat positive" impact on driver retention, while 39% believe it will have no impact. Additionally, 39% of fleet respondents think that drivers are very likely, likely, or moderately likely to use the system. Owner-operator (O-O) response for driver retention or usage were towards the negative end of the scale, but their generally lower preference for DATP may be due to lower profit margins and less available capital. These results indicate the significance of DATP being viewed as an effective tool by drivers and fleets, which relies on practical understanding of its features and applications.

There is much anecdotal evidence that technology acceptance improves with familiarity and training. In terms of how truck drivers would be trained to use the system, all respondent groups desired hands-on or class room training over "system-based self-training". The survey did not solicit information on truck driver compensation models, but it would be interesting to know if DATP acceptance changed based on how and how much a truck driver is paid. Many fleets today provide some form of benefits or rewards to incentivize more efficient operations by their drivers. In stakeholder discussions, one team member has informally heard from fleets with such programs that they have interest in providing driver incentives for the optimal use of DATP systems as well. Future survey work that describes the potential for driver incentives could yield useful insights on important factors shaping driver acceptance.

## f. Platoon Collaboration

Intense competition in the trucking industry makes the question of who to platoon with one of the most challenging aspects of DATP. It is promising that across all respondent groups, 68% to 71% of the trips are on the same routes which allows for more advance planning of potential DATP interactions.

In general, all respondent groups favored platooning within their own company or, in the case of owner-operators, with other O-Os. Doing so generally minimizes conflicts associated with helping a competitor improve their bottom line. It appears that knowledge and trust improves the likelihood that DATP usage would increase over time, as many respondents favored platooning with fleets/trucks with whom they had previously platooned.

Another major issue relating to platooning collaborations is truck location in the platoon. The rear truck gains greater fuel economy benefits than the lead truck. Operational approaches to this will be further investigated in Phase II.

One solution for building truck platoons is to wait at a location for other DATP trucks to arrive. The industry survey solicited information on if and how long drivers and carriers would "delay operations" in order to find and engage other DATP trucks. Again, fleet size had a significant impact on responses, with small fleets and O-Os being extremely unwilling to wait (mean = 95%). With larger fleets ostensibly having a stronger financial condition and time latitude, the response dropped to 54% "unwilling to delay".

However, a change in operations to accommodate the advantages of DATP may not be considered a "delay" per se. In informal discussions, some industry stakeholders have noted that most truck pairing would occur as the result of adjusting dispatch times – so trucks would not be waiting for each other. In Phase II, data will be sought regarding the ability and willingness of fleet managers to change their freight planning and/or alter dispatch.

Finally, it is interesting that only 7% of O-Os were willing to platoon with large fleets, and only 5% of large fleets would platoon with O-Os. This result will inform the design of future surveys.

## g. Industry Financial Expectations

As noted, the trucking industry's average operating margins are slim when compared with other economic sectors. Due to tight margins and limited access to capital, carriers and owner-operators usually weight investment costs, payback periods and net ROIs as more important than the benefits generated by the technologies. In addition, upcoming federal safety mandates are going to force carriers to invest in new technologies (e.g. stability systems) at the same time that other Federal mandates reduce carrier and driver profitability (e.g. new HOS limitations).

The ATRI industry survey solicited both carrier and driver cost and benefit expectations. It should be noted that, due to DATP's position as an emerging and innovative technology, industry respondents likely did not have much insight or knowledge on all DATP costs or benefits that may actually accrue.

In general, smaller carriers desired lower initial purchase costs (mean = $833) but would tolerate higher average maintenance costs (mean = $410) than larger fleets. Large truckload fleets alternatively had a mean "willingness to pay" purchase cost of $1500 per truck, but had considerably lower tolerance for maintenance costs (mean = $250). (For reference, maintenance for electronic hardware/software-based forward collision warning systems was considered minimal based on an FMCSA Benefit-Cost Analysis report[2] which relied on industry interviews.)

*Table 2: Financial Expectations in relation to Fleet Size*

| **Fleet Size** | **WTP Install ($)** | **WTP Maintenance ($)** | **Break Even Period (months)** |
|---|---|---|---|
| 0-6 | - | - | - |
| 7-20 | 1000 | 1000 | 1 |
| 21-50 | 750 | 400 | 18 |
| 51-500 | 1120 | 422 | 10.8 |
| 501-1000 | - | - | - |
| 1001-5000 | 2000 | 250 | 36 |
| 5001+ | 1000 | 250 | 36 |

The interesting stand-out in the "willingness to pay" data was the owner-operator. The O-O respondents had a mean purchase cost of $1,511 and a mean maintenance cost of $497.

*Table 3: "Willingness to Pay" Financial Details*

| **Average WTP per Truck (Install)** |
|---|
| $1,511.11 |

| **Average WTP per Truck per Year (Operation)** |
|---|
| $497.00 |

It can be surmised that O-O respondent's willingness to pay higher purchase and maintenance costs is predicated on the expectation that the DATP system is owned versus leased. When O-Os were asked about subscription costs, beyond purchase and maintenance costs, 67% would not be willing to pay any form of subscription costs.

Break-even or "payback" periods are an important indicator of industry financial requirements. Because of the previously described financial condition of the industry, payback periods are often short. In the case of DATP, O-Os expected a mean DATP payback period of 10 months. Fleet respondents had a mean expectation of 18 months. In all instances, the payback period was considerably shorter than the expected truck turn-over rates that are typically 3-5 years for larger fleets and 5-8 years for small fleets and O-Os. In comparison to the paybacks identified in the FMCSA-sponsored "Benefit-Cost Assessment of Onboard Safety Systems", the continuum of payback time periods ranged from 14 to 36 months. The somewhat shorter expectations or goals for payback periods on DATP may reflect typical industry expectations for efficiency technologies to show more rapid ROI versus other kinds of system investments.

[2] Federal Motor Carrier Safety Administration. Analysis of Benefits and Costs of Forward Collision Warning Systems for the Trucking Industry. Report No. FMCSA-RRT-09-021, February 2009.

## h. Conclusions

When industry economic and operational data is synthesized with the ATRI industry survey on DATP, several business case findings can be highlighted.

Among industry sectors and operational scenarios, larger for-hire over-the-road TL and LTL line-haul fleets along with private fleets are legitimate target markets for DATP investment. They have the financial capabilities and risk tolerance to test and implement DATP. They also have the lane / corridor densities and trip lengths to potentially realize the DATP benefits that accrue from an optimal DATP scenario. In almost all cases, there is little interest in collaborating with competitors, but particularly within the private fleet sector the scale of non-competitors is large. While other sectors and fleet sizes are potential target markets, the larger OTR fleets represent the early adopters that are needed to resolve key challenges and lower adoption prices through economies of scale.

The business case also requires that clear and proven operational scenarios are developed and promulgated to DATP target markets. This means that research needs to validate the roadway types, driving conditions and truck networks that favor safe operation of DATPs and will ensure the promised benefits.

Because the trucking industry is highly communicative, and both DATP benefits and failings will quickly be shared among peers and stakeholders, the empirical data that generates from this and other research must be clear, accurate and disseminated to the key target markets described herein. In particular, to the degree the expected safety and operational benefits are proven, further fleet and driver education is needed.

# *IV. Human-Machine Interface*

The majority of work in this area will occur in Phase II. In Phase I, the OSE team has reviewed literature on topics necessary for performing quality inspection reviewing current platooning technology and for performing evaluations of new technologies. These topics include human factors research of in-vehicle display systems, warning systems, technology acceptance, and human response times, amongst others. Suggestions from this literature review can be found in the 1st quarterly report.

The OSE team has also consulted ATRI's driver and company DATP technology acceptance surveys. The drivers to be used in Phase Two have been interviewed personally before they had observed or been trained on the technology. A similar interview will be conducted post-training and after 1-year to understand the impact from both training and hands-on experience towards acceptance, concerns, and potential pros.

The graduate students and professors that will be working with the truck drivers have begun working on CITI training. This will help ensure that researchers comply with human subjects requirements while collecting data from experimental subjects.

The OSE team has been tasked with reviewing the interface for the platooning technology, provided by Peloton. Literature review has been done on the colors, text size, monitor placement, etc. of such an interface. This information will be used to critique the human-machine interface. Post-critique, changes will be made where agreed upon by the rest of the group. At this point, initial viewings of the interface have been made. The drivers have been able to engage with it while the device was turned off, allowing them to provide guidance on monitor and activation/emergency stop switch placements.

# V. Vehicle Preparations for Phase I

## a.  DRTK/RADAR Testing and Validation

Data was taken in order to compare the relative distance measurements provided by Dynamic Based Real Time Kinematic (DRTK) and a Delphi automotive RADAR.  DRTK works in conjunction with the GPS in order to enhance precision of position data. The main purpose of these tests was to highlight some of the areas where one of the two systems is likely to fail. Tests were performed at NCAT test course in Opelika, Alabama. This is the same site where initial data collection and proof of concept of the prototype system will take place.

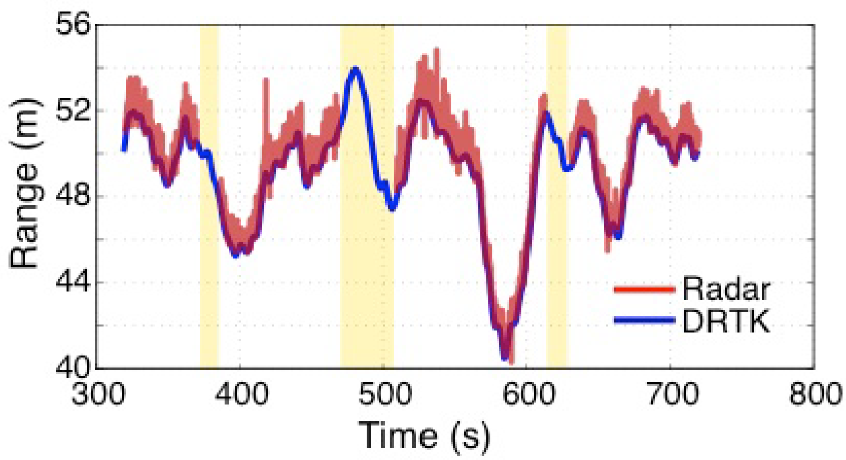


*Figure 2: Relative Distance Measurements vs. Time*

*Figure 3: Satellite View of NCAT Track and Vehicle Path*

*Figure 2* shows a plot of the relative distance measurements vs. time. It can be seen from the figure that the radar measurement is much noisier than the DRTK relative distance estimate. The radar measurement also seems to show a bias compared to the DRTK results although this is most likely inherent of the mounting locations of the systems. This bias will need to be calibrated for future testing.

*Figure 2* also highlights the areas where the radar lost sight of the lead vehicle. These results can also be seen from a bird's eye view in *Figure 3*. A following distance of roughly 50 meters was chosen to expose the radar dropout around turns. In a similar test with a following distance of roughly 35 meters, the radar was able to maintain track throughout the entire course.

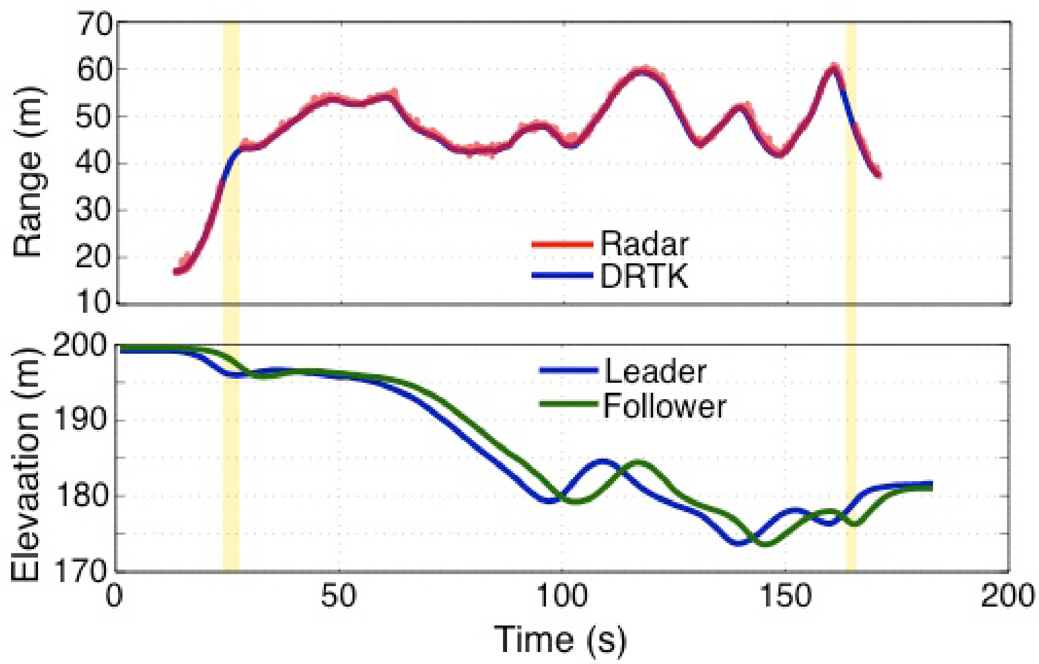


*Figure 4: Elevation and Range vs. Time*

A second test was performed to show radar dropout due to elevation changes between the two vehicles. The main purpose of this test was to gage the radar's tracking performance with large, varying elevation angle. The two locations of track loss highlighted in *Figure 4* were due to non-line-of-sight between the two vehicles. With this being said, the radar showed excellent tracking performance, even with extreme elevation angles.

While dropout in the DRTK solution was not shown in the previous plots, it is known that GPS is likely to lose its solution when faced with minimum sky visibility. This includes heavy foliage, urban canyons, tunnels, bridges, etc. Further testing will be performed to show where the radar prevails in these limited GPS scenarios.

## b. Vehicle Simulation

The GAVLAB has been developing simulations to run two trucks in a leader-follower combination. A simple ACC controller has been developed to simulate a follower truck's ability to maintain a particular distance in relation to the leading vehicle. The simulation does not provide a large amount of analysis in reference to fuel mileage on the trucks right now because the aerodynamic package has not been deployed and the engine mapping for the Peterbilt 579 trucks has not been ported into TruckSim. Nevertheless, a model from engine torque to displacement of the vehicle has been developed. Transfer functions dealing with the vehicle dynamics of the truck have been developed and include torque of the engine to displacement of the vehicle. *Figure 5* shows the acceleration model comparison between TruckSim and the developed model through transfer functions and Simulink. Overall, the graph is acceptable because parameters such as shaft compliance and clutch dynamics were not taken into account and the transfer function model still follows the TruckSim quite closely.

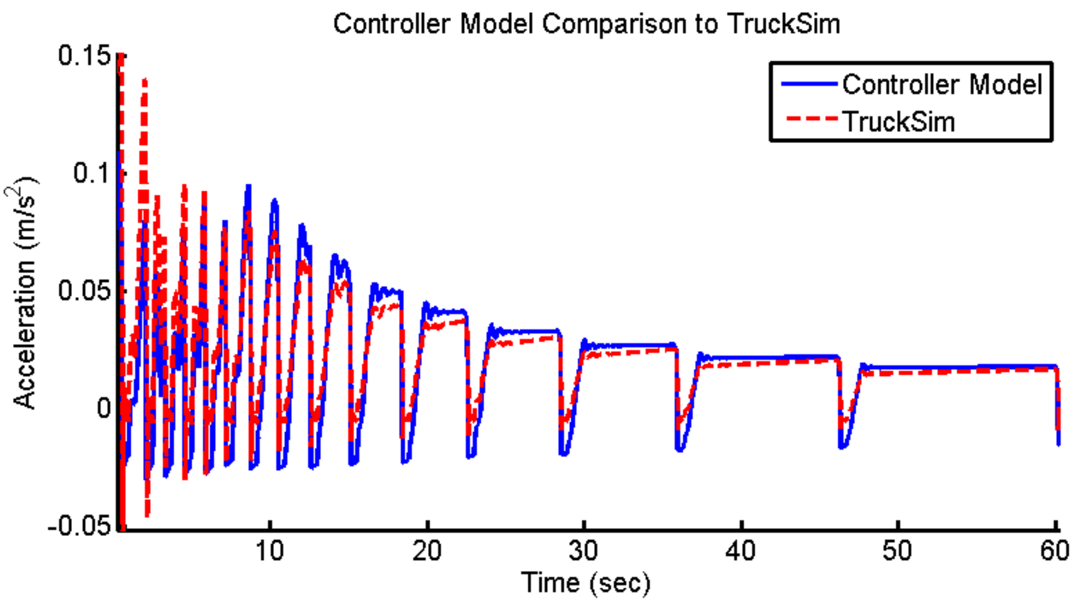


*Figure 5: Controller Model Comparison*

## c. NCAT Test Truck Instrumentation

After initial assessment of the NCAT trucks, it was found that only two trucks within the fleet publish messages from the CAN bus. Of the messages being published, only a few of them are relevant for performing tasks associated with this project. Because the messages published from the NCAT trucks are sparse, data retrieved from trucks used in related truck convoying research for DOD was used for verifying the parsing of the other relevant messages. Currently, the software has been developed for parsing all J1939 messages needed for parameter estimation. This means that the NCAT test trucks were not a viable option for instrumentation and data collection during Phase I.

In parallel, work progressed to acquire test trucks from team member Peterbilt. *Figure 6* shows one of two Peterbilt 579 tractors that were ordered from Peterbilt and delivered to the NCAT facility for instrumentation and testing. Peloton Technologies provided their Bill of Materials needed for system bring-up during Phase I. The materials were purchased and will be integrated with the truck during Phase II.

## d. Plans for Phase II

In relation to Phase II, the system must be set up for testing. With the help of Peloton Technologies, the GAVLAB has acquired all of the necessary materials in order to instrument the Peterbilt 579 tractors with sensors, data acquisition units, and other materials in order to fully prepare the vehicles for testing purposes during Phase II. The following list shows some of the major components needed in order to facilitate safe and effective platooning:

- Radar
- GPS antennas and receivers
- Video camera
- DSRC radios/antennas

- Data acquisition units
- Tablets for HMI

It should be noted here that all of the components that will be installed in the truck must be fastened down for safe traveling while testing any platooning applications. Trailers and loads within trailers must also be deemed capable of supporting full braking stops without shifts in the loads.

In order to make sure that the testing is conducted in the safest way possible, a few initial tests must be conducted. First, the trucks must be driven without any loaded trailer connected to them in order to test the acceleration capability of the tractors, the standard braking system and ABS. Tests will be conducted at the NCAT facility and will range from low acceleration to high acceleration, then 25% full braking power to 100% full braking power. Once the initial braking tests are complete and the drivers are comfortable with the trucks and the testing facility, static testing will be conducted in relation to DRTK GPS for precise positioning. Some of the testing is reliant upon what data is available from Peloton's system. More work may need to be done in order to parse data or acquire more data in order to run the DRTK algorithm. These static tests will also be conducted in parallel with the CSSE testing of the DSRC portion as well as testing of the human subjects of the HMI.

Once the systems components have been properly installed in the trucks and all software has been updated, system preparation on the vehicle will be complete. The project can then move forward to initial on-track testing.

For initial on-track testing, the plan is to run smaller tests on the NCAT track as the 1.7 mile oval track is not necessarily suitable for full fuel runs of a SAE Type 2 fuel consumption test. Also, the NCAT facility will be conducting asphalt tests during the summer of 2015, which involves tearing up portions of the track. This means that for a significant portion of the year only one lane on the track will be available. Testing will take this into account and this will preclude dual lane tests from taking place.

Further testing at a different facility will evaluate system safety and robustness. In order to make sure that the communications systems are operating at 100% a test needs to be run where the trucks are in different lanes running the same direction, but in a leader-follower scenario. The lead truck would then apply the brakes and the following truck will react appropriately.

As previously noted, early testing will be conducted on the NCAT track and analysis of the fuel consumption and the effect that platooning has on it will be conducted for smaller scale tests. The team has broken down some of these smaller scale tests into the following "buckets" in order of increasing complexity:

1. One truck/No trailer
2. One truck/Trailer
3. Two trucks/No trailer/No platooning
4. Two trucks/Trailer/No platooning/On-track
5. Two trucks/Trailer/No platooning/Off-track
6. Two trucks/Trailer/Platooning/On-track
7. Two trucks/Trailer/Platooning/Off-track

Each of these buckets will have a set of tests that will be run for system bring-up, robustness testing, fuel testing, safety, etc. This outline of testing will allow the drivers and team to easily follow a planned testing schedule and complete all testing in a safe and timely matter. It will also help in running multiple tests in parallel and saving on testing hours. In Phase II, each of the "Buckets" listed above will be filled in with different testing procedures.

*Figure 6: Peterbilt 579 delivered to Auburn University at NCAT for testing*

# *VI. V2V Wireless Communications*

## a. Overview of Phase I Research

Vehicle to vehicle wireless networking, or V2V, enables safety information to be shared between two trucks. By using the V2V, data can be transmitted in a more efficient way than relying solely on sensors. With efficient transmissions, CACC can achieve lower inter-vehicle distances. Thus, the main goal of the wireless part of the project is to provide reliable, secure, and efficient networking for the truck platooning application.

The standardized technologies behind the V2V concept are Dedicated Short Range Communication (DSRC) and Wireless Access in Vehicular Environment (WAVE). DSRC is a set of standards that define the behavior of wireless networking in vehicular environment. Despite the fact that most part of the standards has been finalized, there has not been software for each of the layers in DSRC standard set available in public domain. So unlike general networking research where one can start with open source (software) implementations, for DSRC one needs to either find a commercial solution, or build one's own implementation.

As the first step of providing reliable and efficient networking for the platooning application, the team started with implementing the software for DSRC standard set. By implementing it, the team not only provided an option for platooning application to use as the wireless sub-system, but also allowed for an opportunity to carefully explore details of the DSRC standard set. This helped in better understanding the entire V2V communication systems, identifying performance bottlenecks, and thinking about how to improve reliability and efficiency of the communication sub-system of the platooning application in a systematic way.

Different options of hardware and software for each layer of the DSRC standard set were evaluated and choices were made based on feasibility, extensibility, and performance. A fraction of the DSRC standard was implemented. The part that was implemented conforms to the DSRC standard specification, but there was a fraction of the standard that was not able to be completed, specifically some details in Media Access Control (MAC) layer. This includes Outside Context of BSS mode, 1609.2 Security Services, and 1609.4 Channel Switching. This fraction was challenging to implement, but helped in understanding the standards and problems that needed to be solved. This provides a good foundation for optimizing reliability and efficiency of the communication sub-system when switching to a commercial DSRC solution in the next phase.

In addition to implementing the DSRC standard set, a data hub program for distributing messages among different sub-systems of the platooning application was also built. The data hub is language-agnostic, meaning that the sub-systems it supports can be built with different programming languages. It uses an efficient interface to inter-connect critical sub-systems such as DSRC, sensors, and control system, and uses a slightly inefficient but easy-to-program interface for less critical but feature-rich sub-systems such as the user interface.

Integrated tests with the DSRC implementation and the data hub were conducted. Test results showed that this implementation of DSRC along with the data hub does not introduce significant latency. The round-trip latency of messages at a distance of 353 feet is about 2 milliseconds.

## b. High Level Considerations/Evaluating Different Hardware

In evaluating the appropriateness of DSRC hardware and driver software for this truck platooning project, there are very few options in DSRC implementation that are available. Instead of openly working with each other, most of companies involved in DSRC development consider their implementations as important intellectual properties that they will use to compete with other companies. This increases the difficulty for researchers to integrate DSRC implementations into their projects, or to make improvements to it.

Several DSRC solutions outlined below were investigated that may potentially work for the platooning application:

1. Denso, an automotive supplier company, provides DSRC devices. It is an attractive option as Denso works with various automotive companies and standardization organizations. However, they mostly work with automotive companies and have limited resources to work with small research groups. As an unfunded team member, Denso is trying to align resources with Peloton to support this effort. At this time we have been unable to get technical support on drivers and documentation, so it was decided to put this off until they were available.
2. Kapsch is an Information Technology and Telecommunications Company. The team had some of their DSRC radios from a previous project, so a Road-Side-Unit (RSU) was tested. It was able to work at 5.9 GHz with 10 MHz channel width and the SDK that came with it provided some support for WSMP (Wave Short Messaging Protocol). Unfortunately technical support, software tools, and documentations were not available. The SDK was closed source so no modifications could be made.

3. 802.11p Communication Unit from Unex Technology is an all-in-one solution for WAVE/DSRC. It is a mini-PC box that has DSRC, a simple GPS and various functionalities. It has software support for WAVE/DSRC stack. However, the fact that it is a complete solution means the components inside cannot be changed. Furthermore, it was not clear how compliant with standard their devices were. The price was also extremely expensive (~$3,000) compared to other configurations.
4. OBU from Componentality is a mini-PC box that is equipped with DSRC devices. Their support is very responsive and can customize the product a little. Despite this, it is much cheaper (less than $1,000) than the all-in-one solution from Unex, it still suffers from "hard-to-change" problem. In addition, it chooses an adapter in favor of longer transmission range over performance tuning. In the context of the platooning project, transmissions over 1 kilometer are not necessary. It was also not clear how compliant with the DSRC standard Componentality's devices were. From their open-sourced code, it seemed they only had physical layer implemented.
5. DSRC Mini-PCI Adapter (DCMA-86P2) from Unex Technology is the 802.11 adapter used in their all-in-one solution. It is based on the AR5414A chipset, which has been verified by other researchers to be working with a modified 802.11a driver (ath5k). It also has a high rejection Rx filter that gets best frequency response at 5.9GHz and weakens radio signals on other frequencies, which suggests it may suffer less from interference from other channels. The downsides are 1) mini-PCI interface is deprecated by most of hardware makers except some boards equipped with old chipset and router systems; 2) Unex does not provide software support for this.

DCMA-86P2 was attempted as well as implementing a DSRC stack on top of it. Because researchers have been working with them, there are reference and limited source code available online. Also, it aligns well with the project requirements.

At first, Routerstation Pro from Ubiquiti was chosen as target platform. An obvious reason of this choice was it featured three mini-PCI interfaces, which are compatible with DCMA-86P2 adapter. Since it had three interfaces, a secondary 802.11 adaptor for transmitting other data, such as video, was planned to be installed. OpenWRT, a lightweight Linux distribution for networking, was flashed into the Routerstation Pro. The OpenWRT was studied to get familiar with the tools such as package manager and system user-space layout. The system was able to recognize DCMA-86P2 as an 802.11a adapter. However, when porting an 802.11p driver to it, it was found that OpenWRT was not as easily configurable as a normal Linux distribution. As a distribution designed for routers and other embedded systems, it is not easy to develop software for it, thus making it unsuitable as a developing board. For example, custom Linux kernels needed debugging, which may result in an unbootable image. This is easily fixable with a standard Linux PC setup but can be problematic for embedded system like OpenWRT because of the way the operating system is installed.

The decision was made to build some Linux PC boxes for developing DSRC communication protocols. A Nano-ITX architecture board (EPIA N800-13) with 1.3 GHz VIA x86 processor was chosen. Two mini PC boxes were put together, and a DCMA-86P2 adapter was installed on them. Archlinux was installed due to its flexibility on customization of software packages and Linux kernel.

## c. 802.11p Physical Layer

In the DSRC stack, 802.11p is very similar to 802.11a, except that instead of working at 5.8 GHz, 802.11p works at 5.9 GHz. And instead of using 20 MHz channel width, 802.11p has an option of using 10 MHz channel width. The 5.9 GHz spectrum is divided into 7 non-overlapping 10 MHz channels, which provides 7 non-interfering communication media. 20 MHz is considered channel bonding in

802.11p, providing higher through put but reduces the number of non-overlapping channels. To use 802.11p, the group needed to modify existing 802.11a driver to work with DSRC channel requirements.

The group started with an ath5k based driver open-sourced by Componentality. It enables 5.9 GHz on an 802.11a adapter that already works on 5.8GHz, which was the case for the DCMA-86P2 that was being used.

The open-sourced driver was based on an old ath5k version. The kernel that is compatible with the driver was therefore too old. This made it impossible to use it in a recent Linux distribution. To use the driver in recent Linux, and to better understand what modifications needed to be done to traditional 802.11 drivers in order to support 802.11p, an effort was made to port the driver to a recent Linux kernel, 3.13.

The process of porting the driver to Linux Kernel 3.13 was more than several simple code merges. The Linux kernel wireless APIs have changed since the point where the driver was branched, and source directory structure has changed quite a bit. Most importantly, the introduction of regdb formalized regulatory domain settings, making old methods insufficient to enable 5.9 GHz in the driver. In addition to addressing these issues, a logical bug in the driver was found. The bug was fixed and Componentality was notified.

Fortunately, the team was able to successfully port the driver to Linux Kernel 3.13 and enabled 5.9 GHz with the DCMA-86P2 adapter. Two Linux boxes were used to do some simple tests. The two Linux boxes use mini-PCI 802.11p adapters (DCMA-86P2) and 5.9 GHz 5 dBi antennas (Ex-15) from Unex. They were placed close to each other in an indoor environment. Ad-hoc mode was used, running on channel 176 on 5.9 GHz band, with 20 MHz channel width. The iperf test showed a UDP throughput at around 28 Mbps.

Although the 5.9 GHz was enabled in Linux 3.13, it was using 20 MHz channels like normal 802.11a. The 10 MHz channels did not work for this configuration. Although 20 MHz could be considered channel bonding, the team wanted to have the capability of using 10 MHz channels so that more channels would be available to dedicate to different applications.

Since the Linux wireless drivers code got very complicated over years of development, the group took a look at FreeBSD's Atheros driver code “ath”. It was found to be much more approachable than Linux's equivalent. An attempt was made to enable 10MHz channels on 5.9 GHz in FreeBSD and succeeded. As a result, a decision was made to switch from Linux to FreeBSD, so that frequencies can be used which are compliant with US DSRC standard. Since both Linux and FreeBSD have Unix or Unix-like interfaces, it is expected that this switch will not introduce any compatibility issues in application layer and only a few compatibility issues in lower layers. One of the issues is that the ways BSD systems and Linux handle user-space Ethernet frames are different. This means different implementation of WSMP, which is described in next section.

In summary, after trying different platforms, the team settled on FreeBSD and successfully modified the ath driver code to make the physical layer work as an 802.11p device.

## d. DSRC Media Access Control Layer

The DSRC stack defines a MAC operating mode named Outside Context of BSSID (OCB). Unlike standard WiFi where devices join a Basic Service Set (BSS) before they can start communicating with other devices, DSRC uses OCB, which in contrast, does not require joining any BSS. In OCB mode, the BSSID field is set as wildcard values (FF:FF:FF:FF:FF:FF). Standard 802.11a drivers do not have support for OCB mode, meaning it had to be implemented by the team.

FreeBSD ath driver code was studied and progress was made. An obvious characteristic of OCB is that, it uses a wildcard BSSID (FF:FF:FF:FF:FF:FF). This could easily be achieved by explicitly setting BSSID through system interface even in Ad-hoc mode. What requires driver modification is to disable beacon, skip associating, skip authentication, remove synchronization, while still allowing transmitting and receiving of frames.

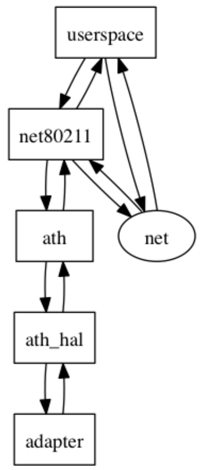


*Figure 7: 802.11 related modules in FreeBSD*

As shown in *Figure 7*, the net80211 module in kernel is the part that is closest to user-space that involves 802.11 networking. This module defines different 802.11 operating modes (Ad-hoc(IBSS), Monitor, Station, etc.). Before an 802.11 adapter can be used, a virtual interface has to be created in one of these modes, and that will be the mode that the adapter is running on. It also handles system calls for the net module, such as transmitting and receiving frames. Since everything related to 802.11 goes through net80211, it is a good starting point for implementing OCB.

Both Ad-hoc and Station mode have a state machine that would initiate association at the beginning. Monitor mode is designed to monitor the nearby 802.11 network, i.e., only receiving is enabled. It seems to be the most similar to OCB but it does not allow transmitting of frames. Changes were made to enable TX (transmitting) path for Monitor mode, and it seemed that the frames were passed to ath module successfully in Monitor mode, but was somehow dropped in ath or ath_hal.

This was unable to be finished in Phase I, but a next step of implementing OCB would be to find out what caused dropping and fix it. After frames are able to be transmitted and received in Monitor mode, a new mode in FreeBSD kernel (based on Monitor mode) can be created to OCB traffic.

## e. Wave Short Message Protocol

Wave Short Message Protocol (WSMP) is a network service layer in DSRC protocol suite intended to replace both Network Layer and Transport Layer in TCP/IP, for the purpose of reducing header overhead. Wave Short Messages (WSM) were implemented as defined in WSMP. This enables the usage of WSMP for V2V communications.

To make it flexible, WSMP was being implemented in user-space. Since WSMP works directly on top of Link Layer, a way to send and receive link layer frames in user-space was needed. FreeBSD provides BPF (Berkeley Packet Filter) to access link layer. The syscall package from Go programming language was used to interact with BPF and send/receive link layer frames.

A library was implemented to parse and encode WSMs. When parsing, the library reads link layer frames from BPF, take the payload, and parse the (variable-length) header according to the DSRC standard. After parsed, the message becomes a struct for easier access by upper layers. When encoding, the library gets a WSM struct from upper-layer, attach the payload with a WSM header encoded according to DSRC standard, and writes the whole thing into BPF.

## f. Diff Protocol

Before looking into j2735, improving communication reliability was essential. One of the ideas was a new transport protocol for time-series beacon-like messages, such as GPS data and vehicle status data. The basic idea was that, beacon-like messages tend to remain same or only slightly change over time. Transmitting complete message every time is inefficient. Instead, only "diff" of messages could be transmitted. This means 1) Only fields in a message that were different last one could be transmitted; 2) for each changed field, only the difference from last value could be transmitted (which is also known as integration compression). The initial design can be summarized as following:

1. There is a light-weight header for each message being sent. A header and its payload compose a diagram. The header of a diagram can contain following fields:

```
+------------+----------------+------------------------------------+
| field name |   field size   |                notes               |
+------------+----------------+------------------------------------+
|    version |   4 bits       | 0x01                               |
|diagram type|   4 bits       | data, diff data, etc.              |
|   msg type | 2 bytes (uint16) | customized according to application |
|         id | 4 bytes (uint32) | incremental identifications        |
|*   base id | 4 bytes (uint32) | base message id for diff data; optional.|
+------------+----------------+------------------------------------+
|    payload |                |                                    |
+------------+----------------+------------------------------------+
```

- "diagram type" includes initial message, diff message, request for initial message, ack, etc.
- "msg type" is different type of message that user wants to send, e.g. GPS Location, Vehicle Status, etc. "msg type" could probably be optionally since transport layer in both IP and WAVE can provide multiplexing. However, if relying on transport layer multiplexing, each message needs a different port number, i.e., in a different connection (in instance of TCP). This is probably not a good thing, considering TCP connection initialization cost.

2. Both end of a connection should keep copies of messages in buffer. Receiving end should keep at least one version (latest seen) and sending end should keep as many as possible.
3. Payload contains either a complete message, or diff of two messages. Semantically, a message is defined by "struct" like this:

```
struct Position { int64 x; int64 y; int64 h; }
struct Vehicle { Position p; int64 velocity; int64 acceleration; }
// It's preferred that data is defined as integers since it's easier to do integer variants.
```

4. Within each message, there could be multiple fields. When updating, not all fields have to change. Based on this fact, diff messages should only contain modified fields. This means a way to address different fields is needed, either by name or by field id. Field id is apparently more space-efficient, so here comes data format within payload:

```
+---------+-----+---------+-----+-------+
```

```
| field_id | data | field_id | data | . . . |
+----------+------+----------+------+-------+
```

In initial messages, data is actual data, while in diff messages, data is differential data.

5. Encoding of data is important for saving space. All integers, including field_id, integer data, and differential integer data, are encoded with variants (https://developers.google.com/protocol-buffers/docs/encoding?csw=1#varints). So that a 7-bit integer takes 1 byte, a 30-bit integer takes 4 bytes, etc. This way, smaller integers take significantly less bits than large integers, while they don't need to have different types. This is rather useful for computing diff of integers. For example, a vehicle moving on high way as 70 mph, moves only about 3 meters per 0.1 second, or 30 meters per second. These can be easily represented in 1 byte instead of 8 bytes int64.
6. If on an unreliably transport (e.g. UDP), the protocol could provide retransmission, but may not need to reliably transmit every single message. In other words, since messages represent status, and status is updated all the time, normally only newest one matters. So the protocol could run on top of an unreliable transport protocol, such as UDP or WAVE's 3rd layer. If so, receiver, upon receiving messages from sender, should acknowledge sender periodically. For the purpose of reducing interference, it's doesn't have to be as frequent as messages themselves. It's like a heartbeat to confirm that the connection is still alive. In ack diagrams, receiver should include the id of last seen diagram, to help sender choose the message version to base diff on.

This proposed protocol was not finished because after looking into j2735, it was found that j2735 is designed to be very compact and bandwidth-efficient. It was believed that the header overhead introduced by Diff Protocol might be greater than the bandwidth it could save over j2735. This might be an interesting research topic in the future, but it was decided that it did not fit well with the platooning application.

## g. SAE j2735 DSRC Message Set Dictionary

DSRC Message Set Dictionary (j2735) is a SAE standard that defines different message types used in V2V and V2I communications. The standard includes many data types that are useful for truck platooning application, such as vehicle motion data and detailed GPS data.

The standard has compact designs. For example, a two-byte space is used to represent both transmission state and speed. The higher 3 bits are for transmission state and lower 13 bits are for speed. This makes it efficient in regarding to communication, but makes programming harder. Thus, a proper library is required for converting between program-friendly data structures and communication-friendly data structures, i.e., an encoding library.

A library for j2735 encoding in Go programming language was begun. In-memory structures were built that were easy to program with, and functions that parsed network messages into the structures, or encoded structures into network messages, were defined.

All required fields in Basic Safety Message (BSM) were implemented. However, those optional fields are needed, especially VehicleSafetyExtensions, which contain RTCMPackage that are used for precise GPS positioning. Therefore, the VehicleSafetyExtensions were added in with the j2735 implementation. However, when attempting to construct a BSM with optional fields, it was found out that the ASN.1 support in Go's standard library was limited. It did not support pointer types on optional fields, as a result, it omitted a field if and only if the field had default values (e.g. 0 for integers, “” for strings). This becomes a problem when it happens that the value intending to be sent is the default value. As a simplified example, suppose vehicle speed is represented as an integer field and it is needed to explicitly describe speed zero in a message.

To solve this problem, other options were considered and the team settled on using a tool called asn1c that compiles ASN.1 specification into C source code. There were some problems using asn1c out of box. Specifically, the codes generated were not compatible with gcc (GNU C Compiler). The problems were fixed by adding –fcompound-names flag to asn1c and by removing some unimportant components from generated C code.

By using asn1c, implementation of j2735 in C is nearing completion. The details in encoding BSMBlob is missing because that is treated as byte array by ASN.1, however, BasicSafetyMessageVerbose, which expands the BSMBlob as ASN.1 types, works very well.

A dummy BSMV is generated, which contains a very large RTCMPackage. The resulting BSMV is 2277 bytes. Compared to the smallest possible BSMV (around 64 bytes), this is very large. Actually it is so large that it will not fit into a single link-layer frame. Since neither j2735 nor WSMP (Wave Short Message Protocol) defines a fragmentation scheme, j2735 messages sent within a WSM has to be small enough so that along with WSMP and MAC headers it doesn't exceed the MTU (normally 1500 bytes). As a result, either the BSMV size will need to be limited by carefully constructing RTCMPackage, only containing necessary information, or a personal fragmentation scheme will need to be defined. If fragmentation is desired, an easy alternative is to use UDP over IPv6 instead of WSMP, but the group thinks that it contradicts the DSRC/1609WG's design.

After talking to Peloton, it was realized that a full-size BSMV would not need to be sent. As a result, the described implementation of j2735+WSMP will work fine.

To find out the capacity of our implementation, stress tests were performed with the WSMP implementation and dummy BSMV message. Two nodes were set up in indoor environment and initialized to channel 176 (@10MHz). The unicast bitrate was 27 Mbps.

As a comparison, iperf was used to test over IP stack. Since the dummy BSMV message is 2277 bytes, if the send rate is 100 messages per second, the bandwidth required would be 2277 bytes/message * 100 messages/second * 8 bits/byte = 1.8216 Mbps. To make the test reflect this load, the packet size was set to be 2277 and bandwidth to be 2 Mbps in iperf, and there was no packet loss.

Then the WSMP was tested, and it was found that the message delivery ratio was only 71% at rate of 100 messages per second. Since the IP stack is able to deliver this traffic load without packet loss, it is believed this is not due to channel capacity. To find out whether the low delivery ratio was due to large message size, smaller messages (1400 bytes) were tested, and the delivery ratio was 99.93% at rate of 100 messages per second. But when the rate was increased to 200 messages per second (which results in roughly same number of frames per seconds as using large messages), the delivery ratio dropped to 63%.

This indicates that there is a bottleneck in the implementation that may prevents from going beyond 100 (large) frames per seconds. The bottleneck is not likely the processing load, because the CPU usages never exceeded 50% when the program was running. The team plans to investigate this to identify and fix the bottleneck.

To sum up, the team started with Go's asn1 package for implementing j2735, then moved to asn1c method due to limitations in Go's asn1 package. Some simple stress tests were performed to investigate communication capacity of the implementation.

## h. Data Hub for Connecting Different Components

The platooning system has many components, including a CAN bus component that reads vehicle diagnostic data and gives instructions for adjusting speed, a component that gets GPS data, a component that does DSRC communication, a component that deals with user interactions, etc. These components need to exchange data with each other. However, different components can be programmed in different languages, or even running on different hosts. The best way to enable this is to design a data hub that connects different components together.

Go was chosen as the programming language for the Data Hub because it has powerful tools to support highly concurrent I/O, is fast to develop, and has execution performance close to C.

The data hub incorporates a subscribe/emit model. Each component can subscribe certain data types from the hub, and can emit (publish) arbitrary types of data. Whenever a component emits data, the hub checks if the type of data is subscribed by other components, and sends the data to them.

To make the hub flexible enough to work with different types of components, different agents are implemented. An agent is responsible for interact with one type of component. So far three agents have been designed. 1) A socket agent which interacts with other agents through local or wired TCP connections. This is used when interacting with programs written other than Go. 2) A HTTP agent which interacts with other agents through HTTP protocol. This is useful for UI as UI is written in HTML/JS; 3) A DSRC agent that uses V2V communication to exchange data with other trucks.

The DSRC agent can easily integrate with our DSRC implementation because they are all written in Go. The HTTP agent can rely on net/http and encoding/json packages in Go's standard library. The socket agent is a bit tricky since it requires a piece of code in target language, C for example, that communicates with the Hub. Data structures also need to be defined in the target language.

The main framework of the data hub has been implemented, including the basic subscribe/emit functionality, DSRC agent, and the Go side of the socket agent.

## i. Performance Testing of the Data Hub

Several round-trip latency tests were conducted with our Data Hub implementation. A Ping/Pong program was built that interfaced with the Data Hub through the socket agent, simulating a module written in a language other than Go. This is explained the architecture in *Figure 8*.

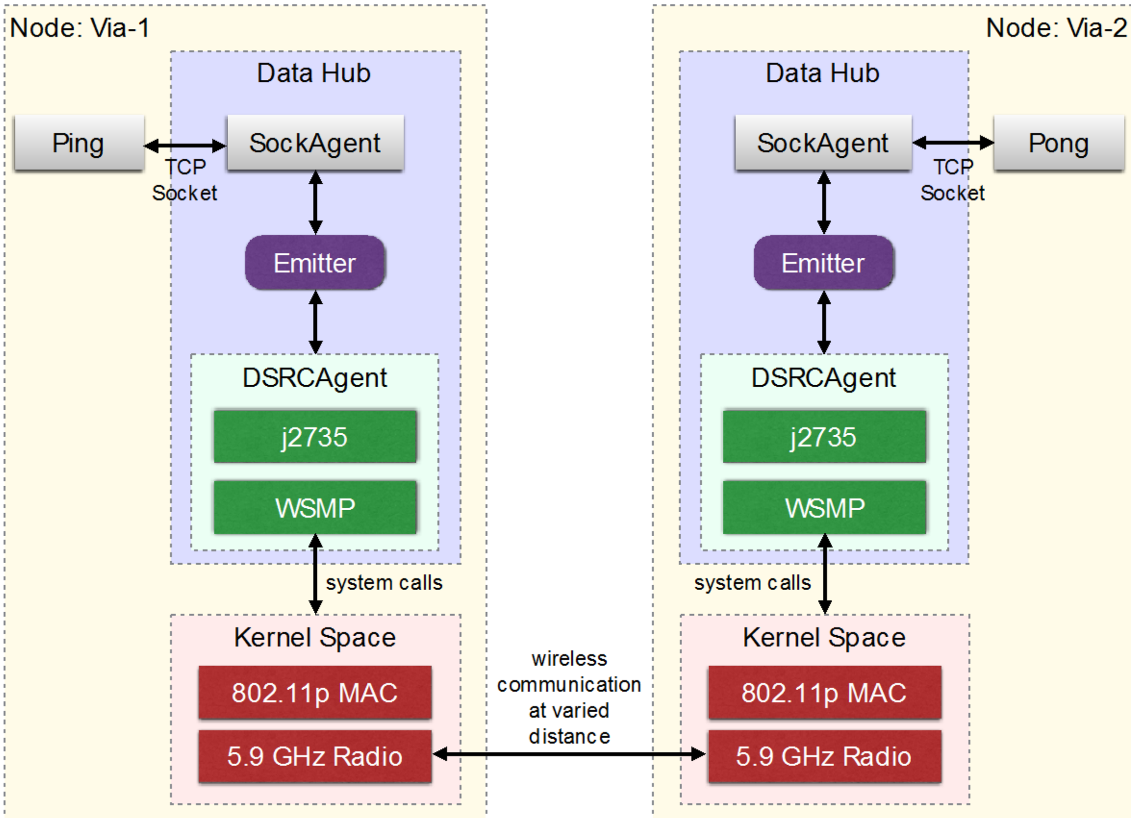


*Figure 8 System Architecture with Data Hub*

On one node (Via-1), the Ping program sends a PING request through TCP socket to the Data Hub. The Data Hub emits the message to all subscribing agents, which includes DSRC agent. The DSRC agent converts the PING request into a Basic Safety Message using j2735 library, passes the BSM down to WSMP, and ultimately sends a broadcasted wireless frame out wirelessly. On the other node (Via-2), the DSRC agent gets the broadcasted frame. It parses the frame and passes up to WSMP layer. The WSMP strips the header out and gives the payload to j2735 library. Since all j2735 messages start with a msgID field, j2735 can easily tell if the payload is a BSM message or other types of messages. If the msgID indicates it is BSM, it parses the payload into a structured BSM. The BSM and a resulting PING request are then emitted to all subscribing agents, which includes the sock agent. The sock agent then sends the PING request to the Pong program through TCP socket. The Pong program, upon receiving the PING request, would respond to the request and send the message to Data Hub. Going through a similar process, the responded PING reaches the Ping program. The duration between the time a PING request is generated in Ping program and the time Ping program gets the responded message is recorded as the round-trip latency.

This architecture was used to test the delay of communication of the whole system, and compare with ICMP ping, which is done within kernel and is considered very efficient. *Figure 9* shows the comparison.

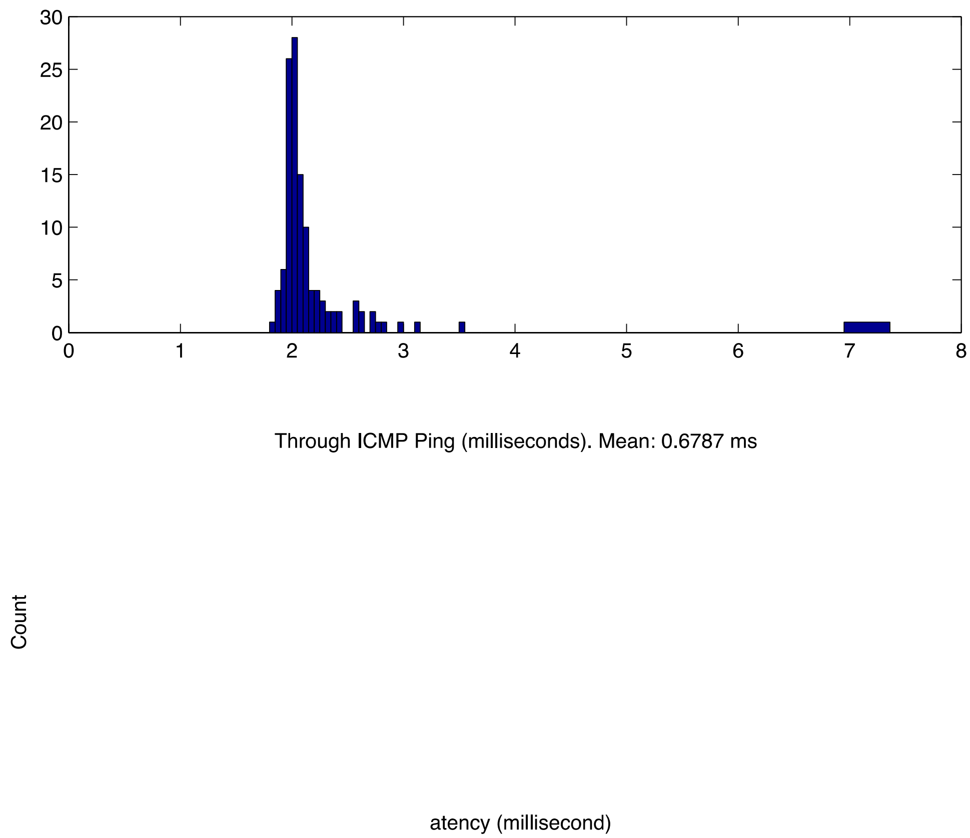


*Figure 9 ICMP Ping v.s. With Data Hub*

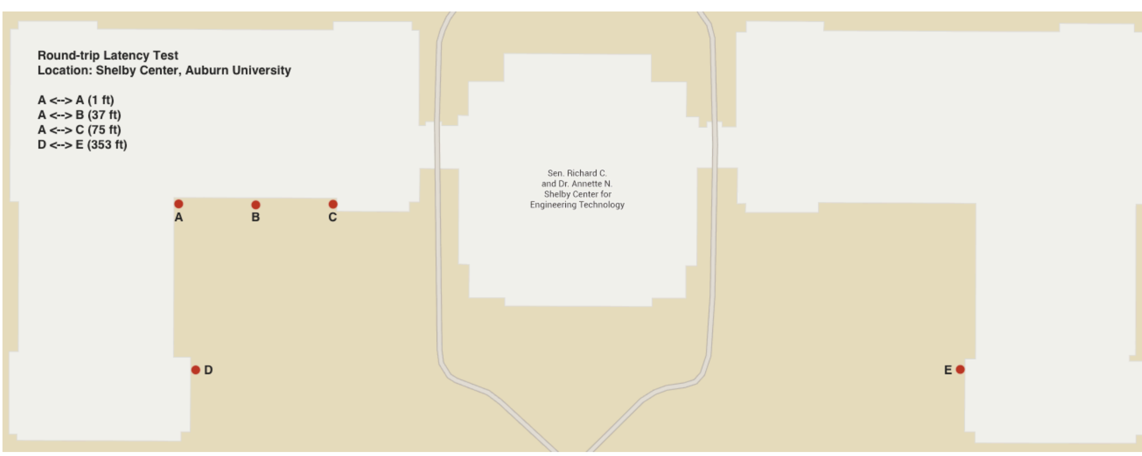


*Figure 10 Outdoor Tests Locations*

As shown in the *Figure 9*, the Data Hub adds roughly 1.5 milliseconds delay to the round-trip, or 0.75 milliseconds to single trip communication. Despite of the added delay, most of the messages still achieved less than 3 milliseconds round-trip, or 1.5 milliseconds single-trip. This is acceptable.

To find out how distance affects round-trip latency, the tests were performed at different locations around the Shelby Center on the Auburn campus, as shown in *Figure 10*. *Figure 11* shows comparison of different distances.

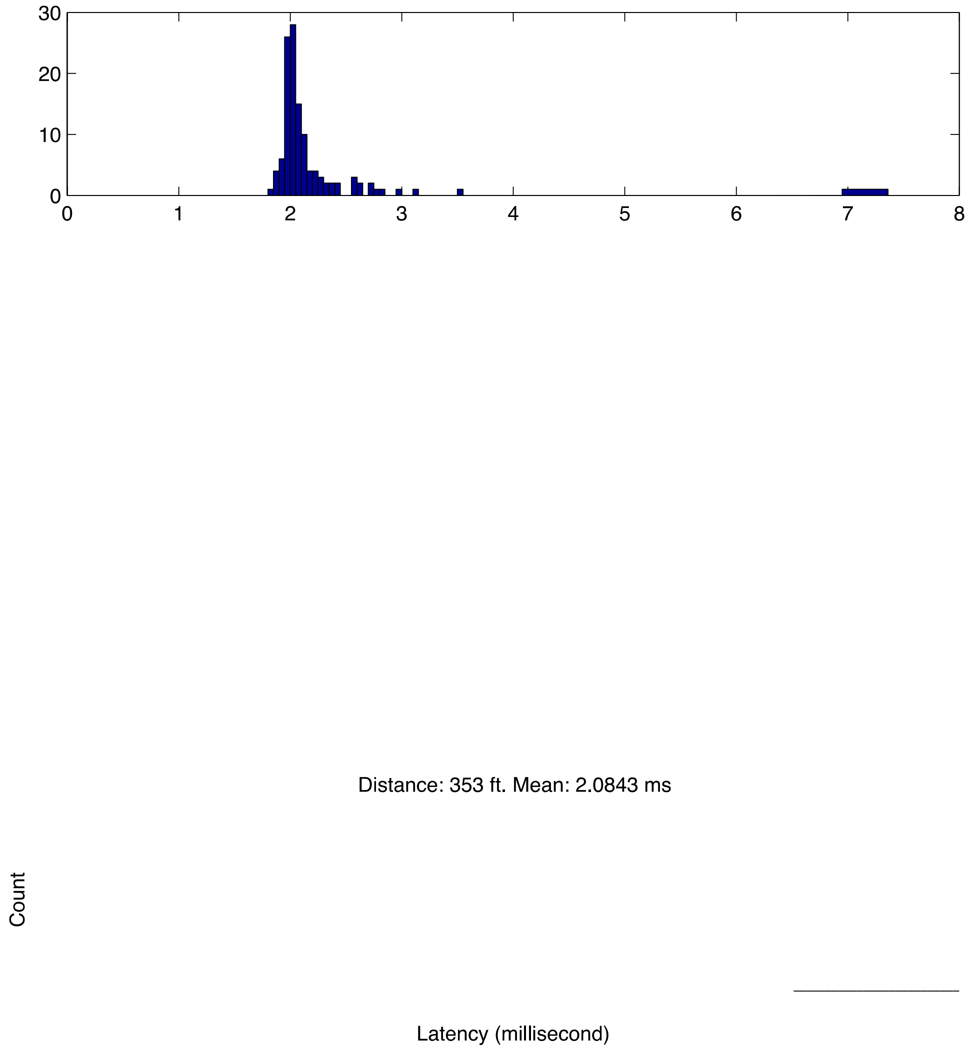


*Figure 11 Round-trip Latency Through Data Hub at Different Distances*

As shown in *Figure 11*, the added distance doesn't add much latency. In fact, some times the increased distance reduces the latency. This might be because the reflex from walls and different structures can cause collision on frames.

These results show that a single message to be delivered to a distance up to 350 feet would have latency of about 1.5 milliseconds. However, the tested environment is still simple. It cannot be said that this will be the latency in real deploying environment. Future tests will investigate this further.

Assuming the 1.5ms latency, and that the interval of messages sent by trucks is 10 milliseconds, the latency is relatively short compared the message interval, and the duration might be mostly relying on the algorithm. For example, if more than two messages are missing, then this indicates disconnection, and then the duration required for determining disconnection is about 20 milliseconds. More data will need to be collected and a more efficient algorithm will need to be developed for this purpose.

## j. Plans for Phase II

Since close work with Peloton will be conducted during Phase II and potential improvement upon Peloton's systems can occur, it is important to adopt Peloton's implementation on DSRC subsystem. Peloton is using Denso's DSRC radios for two types of communications: platooning safety control messages and a video link for transmitting video from leading truck to the following truck. Two Denso DSRC radios are installed on each truck. Based on current knowledge of Denso's DSRC radios, the following studies are planned:

### i. Evaluating on-Road Performance of Denso DSRC Radio

Evaluation of various performance aspects of Denso's DSRC radio including:

a) Stress Throughput Test: test the capability of DENSO devices in terms of throughput (mbits/s). This can be done by using IPv6 stack in WAVE, and running iperf tests between the two nodes. This gives us a rough idea about the channel capacity using the DENSO's devices.
b) Packet Loss at Different Data Rate: measure the packet loss at different data rate. This can also be done with iperf on IPv6 stack.
c) Use BSM/WSMP stack; vary the message size (small BSM vs large BSM) and test a) and b).
d) Measure the message delay of both IPv6 stack and WSMP stack.
e) Vary the distance and test a), b), c), and d).

These tests are to be conducted in an indoor environment first. Then tests will be conducted with radios mounted on the trucks. At last, these tests will be conducted while the trucks are running on the test tracks.

These will give a good baseline of results about capability of Denso's DSRC radios. With these baseline data, mathematical analysis can be performed and an estimate of how it will behave when deployed at scale can be judged. In addition, this allows the group to analyze how platooning applications can affect other DSRC applications.

### ii. Design and Implement Algorithms for Improving Scalability of the Platooning Application

Algorithms and protocols will be designed that improve scalability of DSRC in context of Denso's DSRC implementation. The team will evaluate an adaptive strategy that allows DSRC subsystem to prioritize important safety-related messages differently during distinct driving modes..

# *VII. DATP Inter-vehicle Aerodynamics Research*

Phase I consisted of 3 main parts: Ahmed body development and simulation, single tractor-trailer model development and simulation, and multiple vehicle simulation. The ARG has completed these three sub-phases over the course of the past three quarters of the 2014 calendar year. The Ahmed body was the initial work and was of a validation and verification nature. The single tractor-trailer phase followed and was primarily focused on determining the specific meshing requirements and refinements necessary. The final portion of Phase I was the multiple tractor-trailer simulation. This work developed initial drag trend predictions for use by the research team and resulted in insight into the nature of the aerodynamics of the heavy vehicle configuration and the leader-follower scenario.

## a. Ahmed Body

Phase I began with the development and analysis of a simplified car body, commonly referred to the Ahmed body (Ahmed et al., 1984). The typical Ahmed body geometry is shown below in *Figure 12*. For simulations, the ARG used a model with no rear slope to more closely simulate the heavy vehicle configuration.

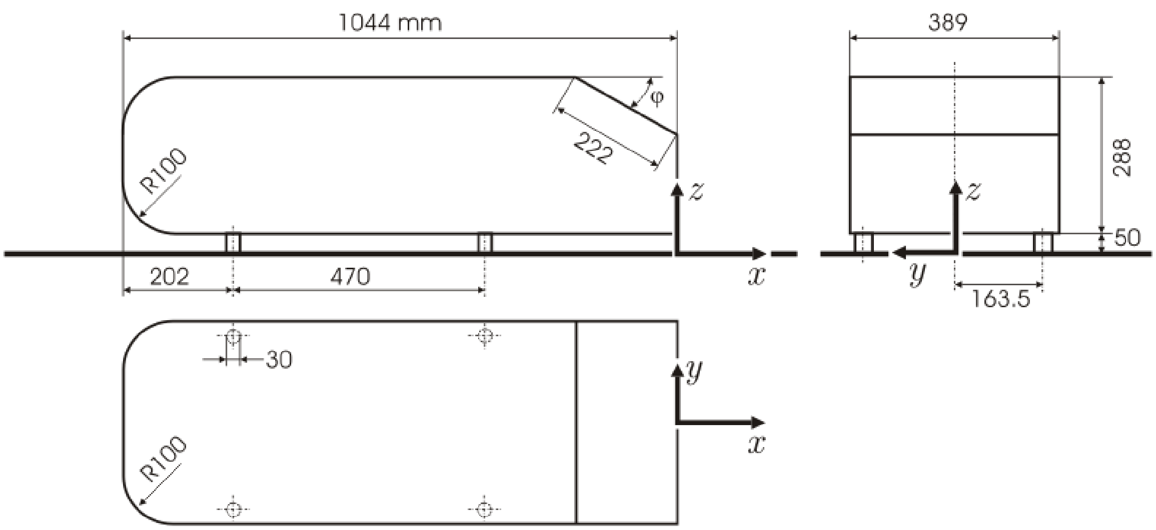


*Figure 12: Simplified Car Body (Ahmed Body) Diagram*

There are several reasons the Ahmed body was chosen as the initial body to model. Firstly, it is a classic bluff body and there has been a large amount of work done examining the aerodynamic forces on this body in low speed flows. Both experimental and numerical data is available for the drag force the Ahmed body experiences. Because there is a wealth of pre-existing information about this bluff body, it is an ideal validation test case for the computational fluid dynamic (CFD) model.

Secondly, the geometry of the body is not only simple to model, but also simple to mesh. This allows rapid generation of low element, high quality meshes to pass to the FLUENT solver. This is helpful not only because it allows solutions to be generated more quickly, but it will also allow for more in depth models in Phase II with refinement and additional bodies in the simulation.

After completion of the mesh, the Ahmed body simulation model was developed within the FLUENT application. Within the FLUENT solver there are a variety of solution settings, thus several permutations of the Ahmed body were examined to determine which model produced the most accurate results. Parameters such as Courant number, solution order, time step size, and convergence tolerance were all modified to determine the effect on solution accuracy.

The factor that has the most effect on solution accuracy, however, is the turbulence model. Flow transitions from laminar to turbulent as the Reynolds number increases and occurs frequently in the real world. Turbulence is a phenomenon that occurs every day, but is not precisely understood. Despite this, it is still extremely important in virtually all engineering flow problems and it must be included in analysis.

Because there is no closed form solution to the Navier-Stokes equations, there is no direct analytical method of determining turbulent flow properties. Thus a numerical approach must be taken to account for the presence of turbulence in a flow. However, due to the irregular nature of turbulence, even numerical models can fail to correctly capture the flow properties and structures.

There are two types of primary types of turbulence models used in industry: Reynolds-averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES). The RANS simulation is inherently a steady state model and is much lower cost computationally than LES. RANS is also less accurate than LES. LES is a conservation of energy based approach and is known to produce more accurate results than a RANS simulation, particularly on bluff bodies. Though LES is more precise generally, an exception is made in near wall regions where losses due to friction are large, in these regions a RANS model will typically provide a better solution.

There were two RANS models examined, both realizable k-$\varepsilon$ (RKE) based. The difference between the models was wall functions: one used non-equilibrium and the other used standard. Both simulations were run using the steady state assumption. Three additional non-steady state, or transient, models were ran: LES, Detached Eddy Simulation (DES) with a Spalart-Allermas (SA) RANS component, and DES with a RKE RANS component. Detached Eddy Simulation, or DES, is a relatively new turbulence that is a LES-RANS hybrid. It uses LES in far field regions, where LES is known to be produce better results, and a RANS technique in near wall regions, where the LES model is less accurate. Combination turbulence models have gained popularity in recent years because they offer more accurate solutions than LES at lower computational cost. Hybrid models do add complexity however, due to the fact that the simulation must transition turbulence models within the domain. The Ahmed body drag coefficient results for the multiple turbulence models are shown below in *Figure 13*.

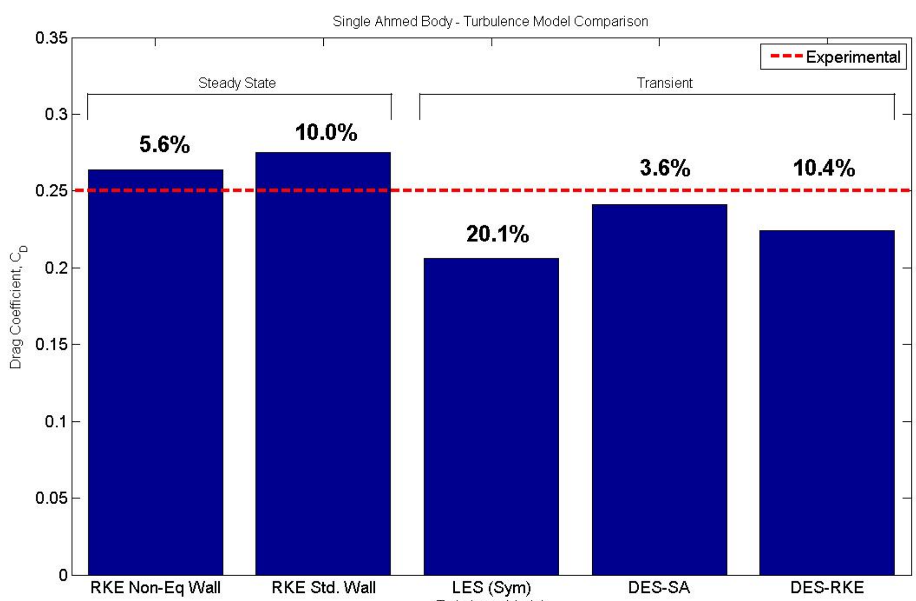


*Figure 13: Turbulence Model Comparison*

As is visible, the RKE and DES-SA models produced the most accurate results, closest to the true experimental value measured by Ahmed (1984). These were the expected results and simulation continued using these models. By the nature of a steady state model, the RKE simulation takes far less time to run than the DES-SA, though this is not a large issue with a smaller mesh such as the Ahmed body, it quickly becomes a factor when the mesh size becomes large (such as with the tractor-trailer model) and the time required for a single RKE simulation becomes several hours.

## b. Single Tractor-Trailer

The single vehicle simulation stage began initially with a CAD modeling of a Peterbilt tractor. A single truck is analyzed first to ensure that the solution is well-refined and grid-independent before moving on to the more time consuming two-truck model. A premade CAD model of a Peterbilt 359 was acquired and de-featured, as shown in *Figure 14*. De-featuring is a requirement for a geometry as complex as a full tractor-trailer configuration because of the disparity of length scale between most features and the overall size of the vehicle. Most nontrivial features require very tight meshing parameters to produce a quality mesh that accurately represents the geometry and will produce an accurate CFD result. This can become an issue if a feature is diminutive when compared to the entirety of the geometry.

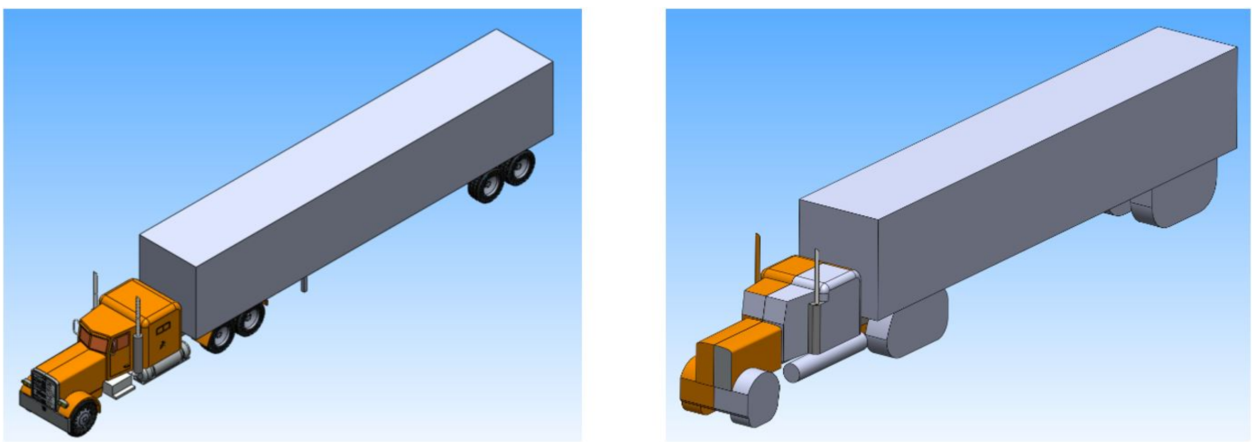

*Figure 14: Side by Side Comparison of Featured and De-featured Tractor Trailer Combination*

When the feature is small when compared to the overall body size, the same parameters that generate a quality mesh will also cause it to grow exponentially. Compounded by the fact that there are several small and complex features on the tractor body, mesh size can quickly get out of hand and become several million elements per vehicle. If time and finite computing resources were not factors in modeling, then these extremely large meshes could be viable. However because a mesh this size provides minimally better simulation results than it's less refined counterpart, it is simply not feasible to simulate a full non-simplified body.

Features that were candidates for removal were small and complex features that changed the flow locally, but did not have an impact on the overall aerodynamic forces of the vehicle. These were features such as the grill on the front, the headlamps, and the side mirrors. Conversely, there are some small features that do have a significant impact on the flow. For example, the windshield is approximately 2 ft in length, but the slope greatly affects the flow on the entire upper tractor thus it is a feature that should not be changed.

After de-featuring was completed, the tractor profile was modified to more accurately represent the test vehicle, a Peterbilt 579. A side by side comparison of the Peterbilt 579 and the modified CAD model is visible below in *Figure 15*. The shown model is the final geometry used for meshing and simulation.

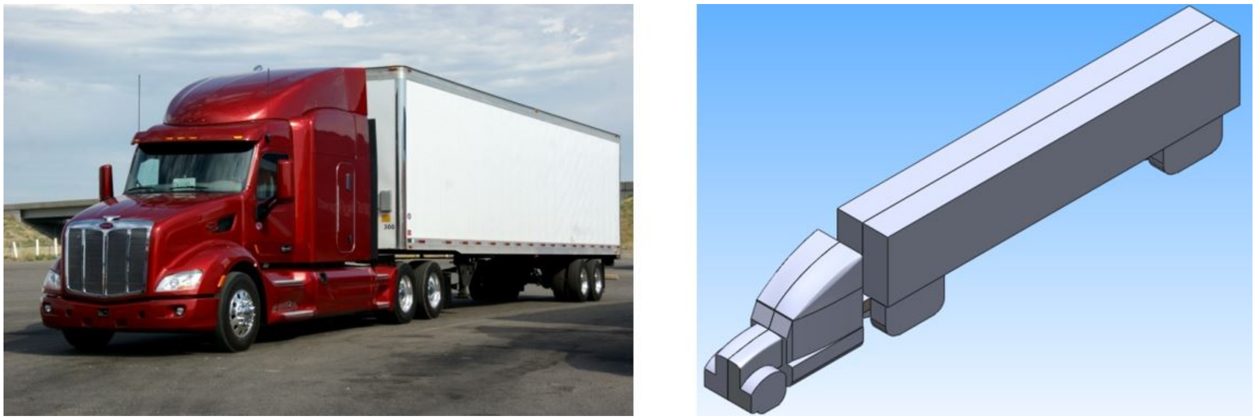

*Figure 15: Peterbilt 579 Comparison*

Once the geometry model was finalized, the meshing process was begun. The program used to generate the meshes passed to the FLUENT solver are generated using ANSYS Meshing (AMSH), which is an unstructured mesher based on the ANSYS ICEM algorithm. AMSH uses a largely automated meshing process, as is typical of unstructured meshing. In the most general of senses, the unstructured meshing parameters can be set independent of the model geometry. The user can specify global meshing constraints, such as maximum and minimum element size, allowable growth factor, and cell aspect ratio and AMSH can generate a mesh that conforms to the input geometry.

In the majority of cases, however, the mesh will be of insufficient quality to produce an accurate solution. In these situations, more specific input must be given, such as refinement regions and inflation surfaces, each of which have additional parameter requirements. Furthermore, with complex geometries such as the tractor-trailer configuration the meshing algorithm will often be unable to produce quality meshing around features that interface, such as the slope of a wheel intersecting the ground plane. The reason for this is that AMSH is essentially attempting to create a volume mesh in a space that converges to a single point or line. While it is possible to define “pinches” that cutoff the tips of these regions, it is often more accurate and more convenient to make model modifications to work around such limitations.

The main metric for evaluating mesh quality used for this analysis is element skewness. Skewness is a measure of how “skewed” a cell is from the equiangular equivalent. In an unstructured mesh, the preferred element shape is a hexahedron, a polyhedron with six faces. A cube is an example of a regular hexahedron with zero skewness. (all the angles are equivalent) However, shearing the cube would create a rhombohedron, which has an associated skewness when compared to the original cube. A visualization of element skewness is provided in *Figure 16*.

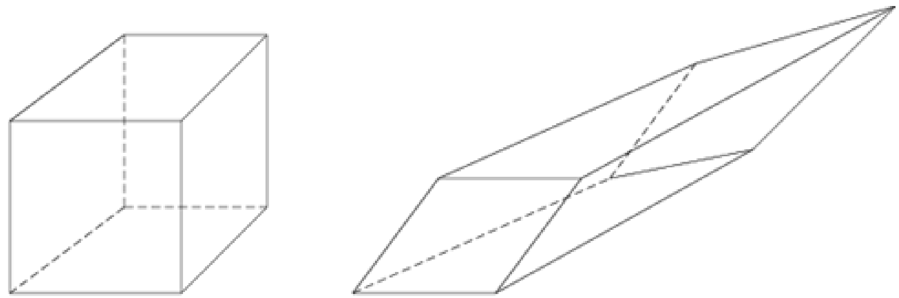


*Figure 16: Element Skewness*

Skewness is an apt indicator of mesh quality because it represents the amount of deviation from a structured mesh that is present. Because Cartesian / structured meshes are inherently more accurate than unstructured meshes, lower skewness translates to higher quality. Thus the average element skewness indicates the overall mesh quality.

A second skewness metric is the maximum element skewness. The maximum possible skewness is 1, which would represent an element that has collapsed upon itself, effectively creating a 2D plane, which is unphysical and unsolvable. Unstructured solvers, such as FLUENT, can handle very local high element skewness and still provide accurate results. The ANSYS Fluent algorithm can take an element skewness of approximately 0.95 without becoming unstable and diverging. Thus the maximum element skewness within the domain indicates the acceptableness of the mesh.

For the heavy vehicle meshes generated the average element skewness is approximately around 0.25 and a maximum skewness larger than 0.90 was considered to be unacceptable to pass to the FLUENT solver.

The results from the single body simulation showed a drag coefficient of approximately 0.54 at a vehicle speed of 30 m/s (approximately 65 mph). This was the nominal value that was then used in the multiple vehicle model to determine drag reduction. There was not experimental data available for verification of this drag, however, it can still be used confidently to develop drag trends as the simulation consistently produces this drag force result. Thus, even if the drag produced is not the correct drag it can still be used to generate incremental or relative drag reduction models that provide insight into the vehicle spacing-drag correlation.

## c. Multiple Tractor-Trailer

After completion of the single vehicle analysis, a two-vehicle model was developed. The initial spacing between vehicles was set at 36 ft and then varied in increments of 9 ft. Thirty-six feet was chosen as the initial spacing due to the fact that there was available test data from Peloton and 9 ft was chosen as the increment because it is approximately 1/8 of a vehicle length (70 ft). Test cases were then generated for separations from 1/8 body length (9 ft) to 1.5 body lengths (108 ft). The drag results are shown below in *Figure 17*.


*Figure 17: Two Vehicle Drag Reduction as a function of Vehicle Spacing*

These results provide a significant amount of information about the drag-spacing relation. Though there is some variation past the 72 ft separation, the drag appears to asymptote at this point to no drag reduction for the lead vehicle and approximately 25% drag reduction for the second vehicle. This is an interesting result due to the fact that the follower vehicle sees significant drag reduction as far as 1.5 body lengths away from the lead. The ARG is currently investigating this phenomenon to confirm this outcome. It is also interesting that even as far away as 40-50 ft, the follower can still have a nontrivial effect on the leader's drag force.

The drag reduction the follower experiences comes primarily from the reduced average directional freestream velocity. As seen in *Figure 18*, at a vehicle spacing of 108' the velocity magnitude incoming at the follower vehicle is nearly 50% of the freestream velocity the leader experiences. This results in a very large reduction of drag force on the vehicle, as it is proportional to the square of the resistant velocity. This is then reflected in the drag coefficient, which is normalized by the true freestream velocity. This is indicative that as far as the disturbance caused by the leader propagates downstream, the follower will still see a large drag reduction, giving fuel savings even at large separation distances.

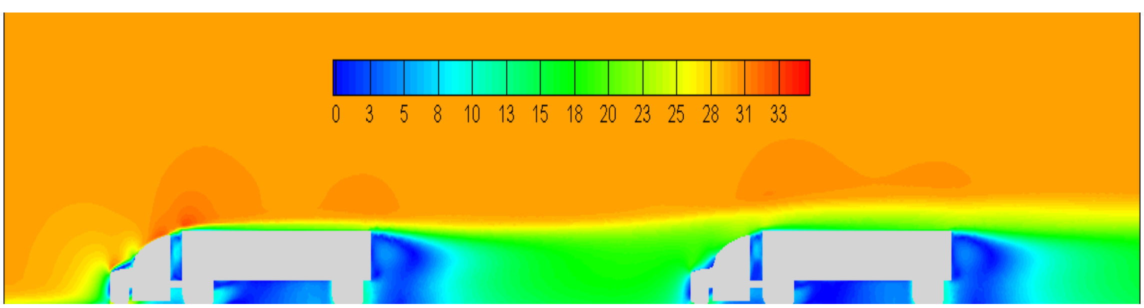


*Figure 18: Velocity Magnitude (m/s) for a separation distance of 36 ft*

The drag reduction seen by the leader vehicle comes almost exclusively from wake interference by the follower vehicle. *Figure 19* depicts the streamlines and flow structure behind the lead vehicle at 108 ft separation (when there is no influence of the follower on the leader). It is visible that there are two distinct vortices that form and create drag: the upper vortex from the flow coming off the upper surface and the lower vortex created by the flow under the vehicle. The lower vortex is much tighter than the upper vortex and has a larger magnitude. The wake drag of the vehicle, which constitutes a large portion of the overall drag, comes from the two vortices.

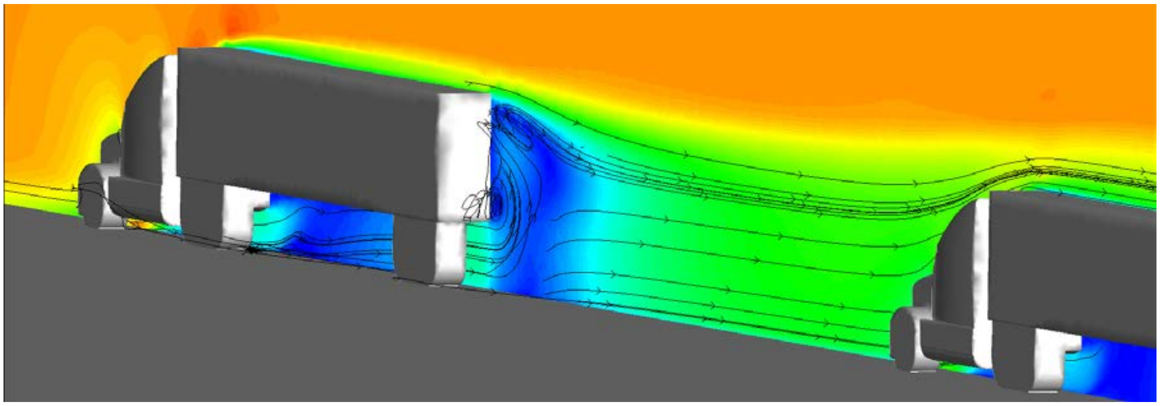

*Figure 19: 108 ft Separation Streamlines*

When the follower vehicle is close enough to interfere with these vortices, the wake drag is greatly reduced as they are unable to properly form and “pull” at the vehicle. This obstruction in vortex formation is especially visible at a separation distance of 18 ft, as shown in *Figure 20*.

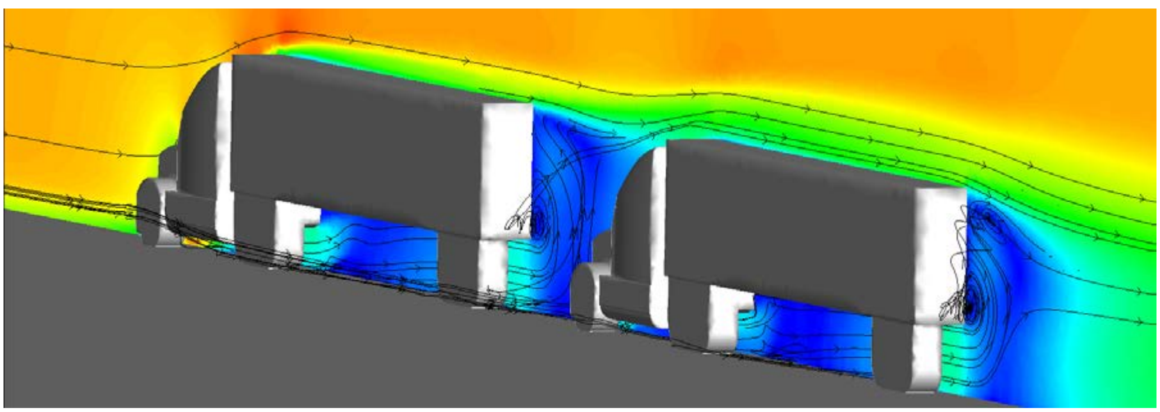

*Figure 20: 18 ft Separation Streamlines*

Though this distance is likely too close even for the automated system, it is still an excellent simulation case as it provides superb visualization of the leader-follower flow interaction. It can be seen that the lower vortex still forms, though it is of a lower magnitude. It is likely that this vortex will always form due to the low speed flow coming from the undercarriage of the vehicle. The upper vortex, however, cannot form at all and flow that would have re-circulated in this vortex is pushed over the second vehicle.

Overall the simulations are extremely promising, as the follower vehicle appears to see large amounts of drag reduction, even at larger distances. At closer distances these savings are compounded by lead vehicle drag reduction. This is also encouraging because the distances required for leader fuel savings do not appear to be below the margin of safety for the DSRC system to be operated. These results are consistent with other studies considering two aerodynamic bodies in a platoon (Pagliarella et al. 2007, Jootel, 2012).

The ARG is currently re-examining the single tractor-trailer case. The primary reason for the return to the single vehicle is to gain insight into the flow structures in the vehicle wake. Several cases are being examined with highly refined grids in the wake regions and behind the vehicle. Because the drag reduction the second vehicle experiences is due in large part to the lower average directed velocity, knowing more about the expected flow field behind the first vehicle is extremely useful. Particular quantities of interest are the length of the flow disturbance and velocity profile. These parameters will allow for better predictions of the second vehicle drag reduction and the following distance where the second truck sees no benefit.

## d. Plans for Phase II

Due to the complex geometry of the tractor-trailer vehicle, meshes that are high enough quality for CFD quickly become extremely large. This is problematic because of hardware limitations, large meshes take large amounts of RAM. Thus it is unfeasible to run a tractor-trailer mesh with more than 3 vehicles on existing ARG resources, limiting the ability the gather drag trend information about larger platoons.

The Ahmed body, however, does not suffer from this deficiency. Because of its simplified nature, meshes of 5-6 vehicles can be easily developed. Simulating several Ahmed bodies will not give information about the tractor-trailer configuration, but it will allow the development of drag reductions trends for multiple vehicle configurations which can be applied to tractor-trailer environment.

# *VIII. Finding Linking Partners: Analysis and Methods*

## a. Introduction

Platooning operations promise increased fuel savings and improved safety through CACC technologies. In this case study, we analyzed truck fleet data to determine the impacts of platoon formation on several key metrics, including the number of platoons that may be formed from historical truck routes, the maximum size of any platoon formed, and the total time lost as a result of trucks slowing down to form a platoon.

The test data, provided by the American Transportation Research Institute (ATRI), captures the location of each truck in fleets who have partnered with ATRI to share location information at various times of the day. Auburn University was provided two sets of data from ATRI, referenced below as "NDFT1" and "NDFT2," from two separate truck fleets (i.e. fleets owned by individual companies). Each dataset describes individual truck locations from a given fleet that were recorded over an eight-day period along an approximately 300-mile long stretch of Interstate 94 between Dickinson and Fargo, ND. Therefore, the dataset serves to support an analysis of “within-fleet” platooning, which is seen as a likely early deployment scenario.

This particular road segment was chosen for the initial analysis due to its relatively low traffic volumes (resulting in a data set of manageable size) and limited ingress/egress points (allowing the consideration of trucks that remained on the corridor for an extended distance), as shown in *Figure 21*. Thus, this data set provided a means for testing and evaluating the optimization algorithms, while also providing insight into the impacts of platooning operations. Data from highway corridors with higher traffic flows and numerous intersections with other highways will be analyzed in Phase II of this project. The analysis described below assumes that all of the trucks in the datasets are platoon eligible.

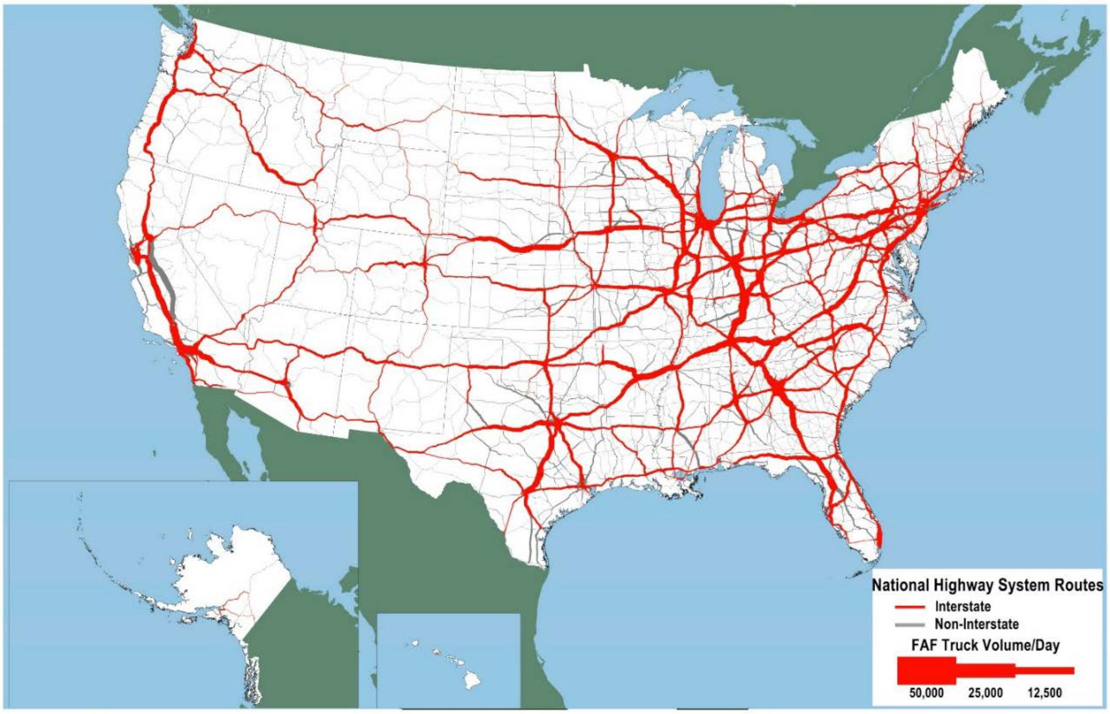


*Figure 21: Average daily long-haul freight truck traffic on the National Highway System in 2007. Source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Managment and Operations, Freight Analysis Framework, version 3.4, 2012.*

New optimization algorithms were developed by the researchers to determine which trucks should join a platoon, given the starting location of each truck. In particular, our analysis provides preliminary insights into the following metrics:

- Percent of trucks that join a platoon,
- Number of platoons formed,
- Number of trucks that were time delayed due to platooning operations,
- Number of platoon formation operations (number of times vehicles adjusted speed to join a platoon),
- Maximum platoon size at any given time,
- Total time lost for trucks that platoon,
- Distance traveled within platoon by individual trucks,
- Percent of total distance traveled within a platoon, and
- Total (estimated) fuel savings resulting from platooning.

The newly developed optimization algorithm is initialized with the location of each truck from the test data. The algorithm requires four key parameters. To form a platoon, a candidate lead truck may decelerate to fall back to join a trailing truck. In our analysis, we consider lead truck adjustment speeds of 5 and 10 miles per hour slower than the current speed. Similarly, the trailing truck may accelerate to join upstream trucks, with a trail truck adjustment speed of either zero or five miles per hour faster than the current speed. To limit the number of vehicles in a given platoon, the maximum platoon size parameter was set to two, three, or an unlimited number of trucks. Finally, the expected net fuel savings associated with forming and operating the platoon dictated the decision to couple trucks into platoons. We employed a Percent reduction in fuel cost for a platoon of either 5% or 10%, consistent with the published works of Larson et al. (2013) and Liang (2014). To improve the tractability of the models in this preliminary analysis, all vehicles in a platoon are assumed to realize the same fuel economy benefits.

In Phase II the models will be enhanced to explicitly consider the differences in fuel economy benefits based on position within the platoon (e.g., the lead truck will enjoy approximately half the fuel savings of a trailing truck).

Letting $d_1$ be the distance from the trailing truck to the location where it meets the lead truck, $d_p$ be the distance traveled in platoon, $v_1$ and $v_2$ be the respective trailing truck and lead truck velocities, $v_p$ be the velocity of the trucks while in platoon, *s* be the percent reduction in fuel cost for a platoon, and $\Delta v_1$ be the trail truck adjustment speed parameter value, we may determine whether trucks can feasibly platoon. For Equation (1), $F_1$ is the fuel cost and $\Delta F_1$ is the fuel increased cost, meaning the extra fuel energy incurred from accelerating. Note that $\Delta F_1$ would be zero if the truck remains at a constant speed. The fuel cost, $F_1$, is measured by $.5d_1v_1^2$ (Larson et al., 2013). Thus, Equation (1) is simply the fuel cost of traveling at the faster speed ($v_1 + \Delta v_1$) minus the fuel cost of traveling at the normal speed ($v_1$). Extending the idea of fuel cost to Equation (2), we obtain the equation for S, the fuel benefit from platooning. The first term of Equation (2) describes the fuel cost of truck 1 traveling at its normal speed for the distance that the trucks would have been in platoon if speeds were adjusted accordingly for platooning. Similarly, the second term describes the fuel cost of truck 2 traveling at its normal speed for the distance that the trucks would have been in platoon if speeds were adjusted accordingly for platooning. The third term describes the fuel cost of both trucks traveling at a common speed in platoon over the distance that they would platoon with a discount *s*. Thus, the discounted fuel cost from traveling in platoon is subtracted from the individual truck costs to get the fuel benefit from platooning.

$$\Delta F_1 = .5d_1((v_1 + \Delta v_1)^2 - v_1^2) \tag{1}$$

$$S = .5v_1^2 d_p + .5v_2^2 d_p - (2 - s).5v_p^2 d_p \tag{2}$$

If the benefit from platooning is larger than the fuel increased cost, then the platoon should be formed and the savings percent earned are obtained by calculating one minus the quotient of the expense incurred in the event of platooning over the expense incurred without any platooning or speed adjustments.

While the results of this preliminary analysis are not necessarily indicative of more general conditions, they form a foundation for the more thorough analysis to be conducted in Phase II of this project. In particular, Phase II efforts will involve a larger dataset and differing road segments. However, through this Phase I effort we have established and tested algorithms and a scalable system architecture that will support more rigorous future analysis.

## b. Summary of Key Findings

Before providing a detailed analysis of the results generated by the optimization approach, we offer a few interesting observations. First, the percentage of fuel savings is only sensitive to the percentage of fuel reduction parameter and road saturation. This is the most surprising result, as the median savings is approximately 4%-7% regardless of the maximum allowable platoon size and adjustment speeds. It appears that the savings are not impacted heavily by changes in parameter values. Second, the lead truck adjustment speed has a significant influence on the number of platoons formed. In particular, an increase in the lead truck adjustment speed (deceleration) results in the formation of additional platoons. However, a large lead truck adjustment speed also corresponds to increased time delays for platooned trucks.

One surprising result is that a trail truck adjustment speed of zero results in a greater number of platoons formed than when the trail truck speeds up by five miles per hour. The reason for this is that the cost of speeding up is a steep enough penalty to restrict platooning opportunities. However, a trail truck adjustment speed of five miles per hour enables longer distances traveled within a platoon by catching up to the platoon faster. A larger trail truck adjustment speed also decreases the time delay associated with platooning.

As the maximum platoon size increases, the number of platoons formed tends to decrease. This tendency is intuitive since large platoons absorb the platooning opportunity that could otherwise be distributed among several platoons of size two or three. Also, the percent of trucks that join a platoon tends to increase as the maximum platoon size increases. This is also intuitive since larger permissible sizes create more platooning opportunities.

Finally, the road saturation has a profound impact on the level of platooning opportunity. *Figure 22* compares NDFT1 and NDFT2 by showing how many pairwise truck distances were within five miles, projected at 12:00 pm. on each side of the road. In particular, NDFT2 boasts more trucks with small pairwise distances than NDFT1, which is one reason that the results show more impressive platooning behavior for NDFT2.

One of the core project research questions addresses the relative likelihood that trucks will be able to find platooning partners, given typical distributions of trucks on highways. These findings show that, with this real-world dataset (which does not include all trucks on this highway section), formation of two-truck platoons among platoon-eligible trucks was 3-7% for NDFT1 and 30-45% for NDFT2. The differences depend on the parameters employed by the platoon formation model (e.g., allowable adjustment speeds for leading or trailing trucks). We find that trucks forming two-truck platoons in the NDFT1 dataset traveled within a platoon between 30-60% of the distance of the 300-mile road segment, on average. Trucks joining two-truck platoons in the more densely populated NDFT2 remained within a platoon between 55-75% of the road segment, on average.

Importantly, next phase work will incorporate differences in fuel economy benefits depending on platoon position. Therefore the results presented here should be considered preliminary.

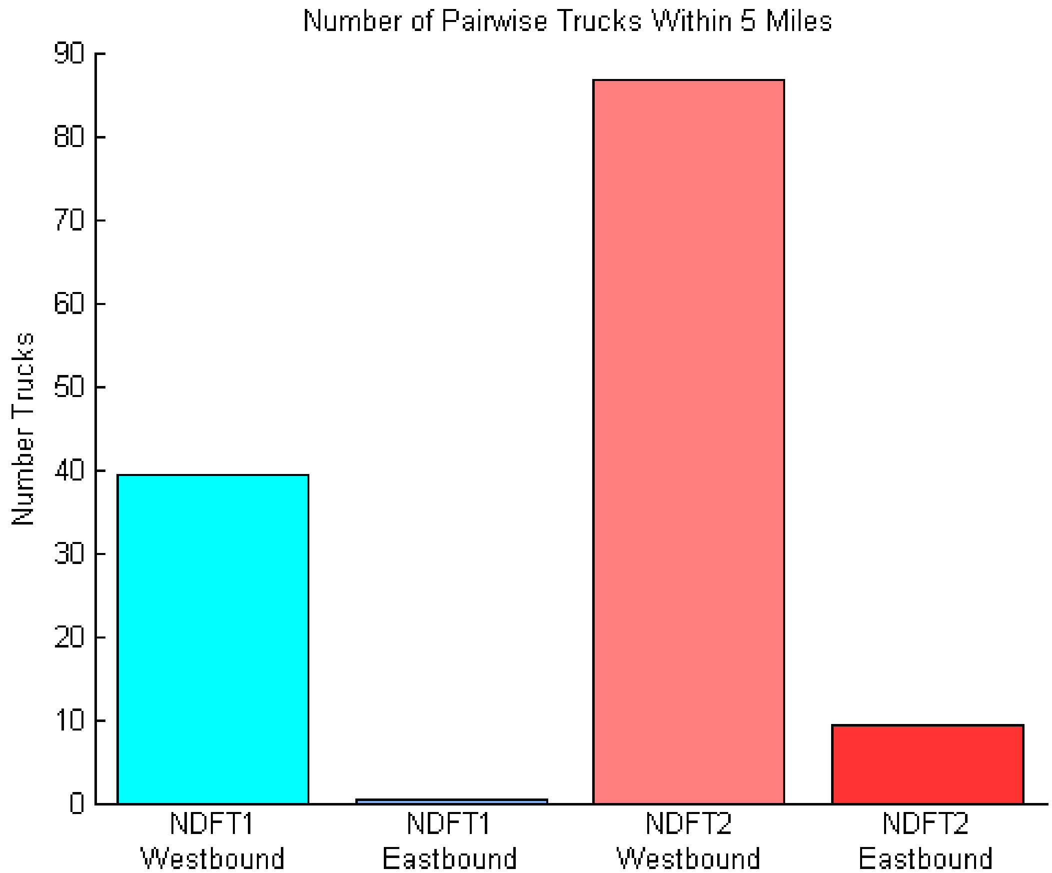


*Figure 22: NDFT2 has much higher road saturation than NDFT1*

The rest of this section is organized as follows. The experimental design section describes the efficient procedure used to analyze the data and obtain interesting metrics. The body of the report discusses individual metrics obtained along with parameter comparisons. Finally, the report concludes with a brief future outlook.

## c. Experimental Design

ATRI provided two datasets with columns of information describing truck identification, time logged, and corresponding speed, latitude, and longitude. Each dataset contains eight days of data. Each day presents 24 hours of data. The program was run for each day, and the results were aggregated into useful platooning information over the entire week. A set of non-ATRI data generated only for the purpose of presentation is provided in *Table 4*. The data do not explicitly specify heading, but this may be determined by tracking the relative location of each truck over time. Automated scripts were developed to infer truck heading and intermediate truck locations (between timestamps). These scripts will facilitate future testing on additional data sets. *Figure 23* summarizes the process of translating the raw truck location data into a form amenable for detailed analysis.

*Table 4: Notional representation of data fields provided by ATRI.*

| Truck ID | Timestamp | Speed [mph] | Latitude | Longitude |
|---|---|---|---|---|
| 3436436 | 1/2/2013 00:00 | 65 | 97.83948 | -102.433 |
| 89734 | 1/2/2013 04:55 | 66 | 96.38923 | -102.444 |
| 4231375 | 1/2/2013 05:21 | 68 | 96.77390 | -102.446 |
| 902357 | 1/2/2013 23:39 | 66 | 96.09458 | -102.523 |

All bar graphs represent data averages. In particular, each dataset contains eight days of data. Each day was analyzed separately, the results were aggregated into one week, and the average values were computed for the bar graphs.

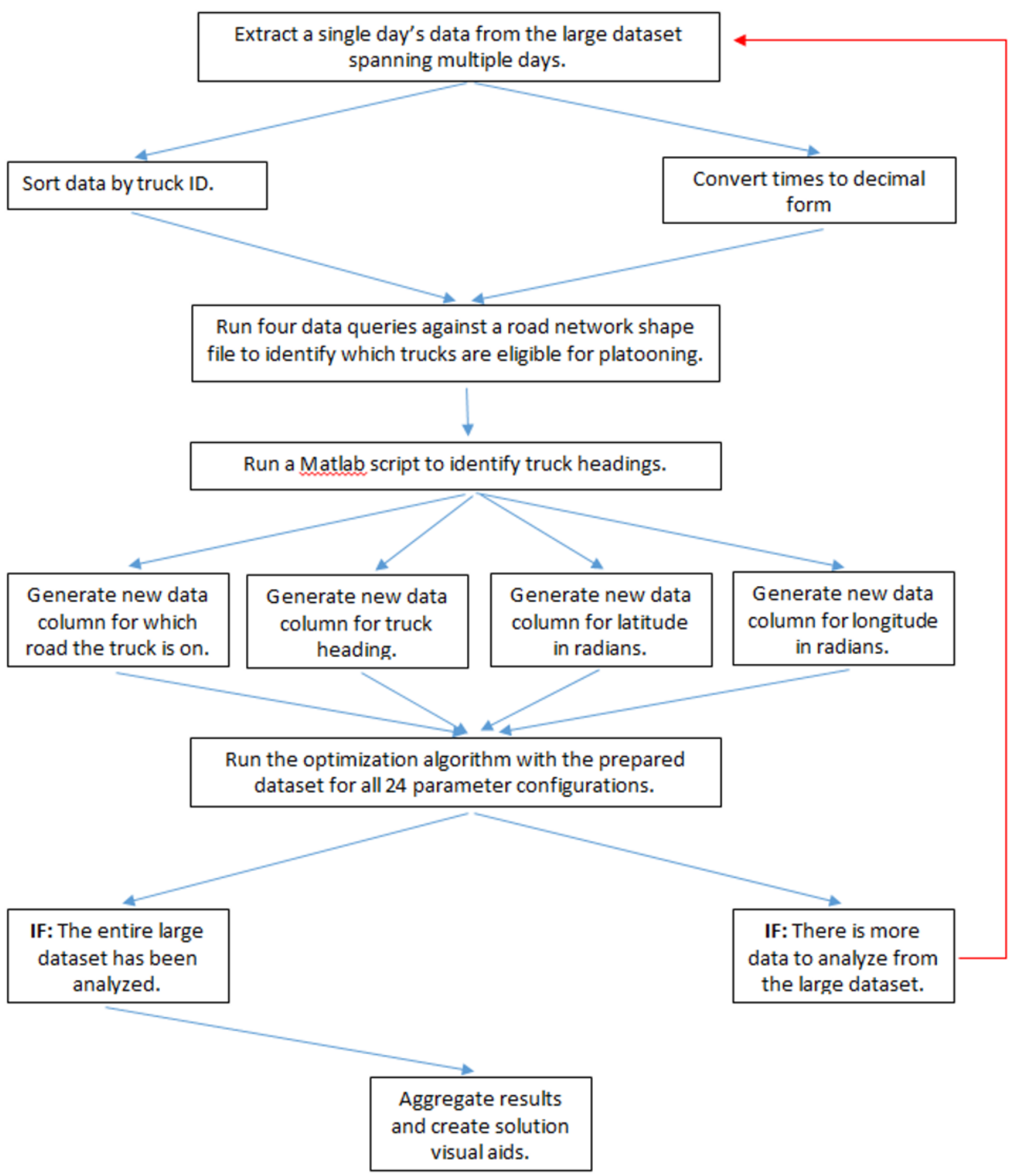


*Figure 23: Analysis Process*

## d. Percentage of Trucks that Joined a Platoon

This metric is measured by the quotient of the number of trucks that joined a platoon over the total number of platoon-eligible trucks.

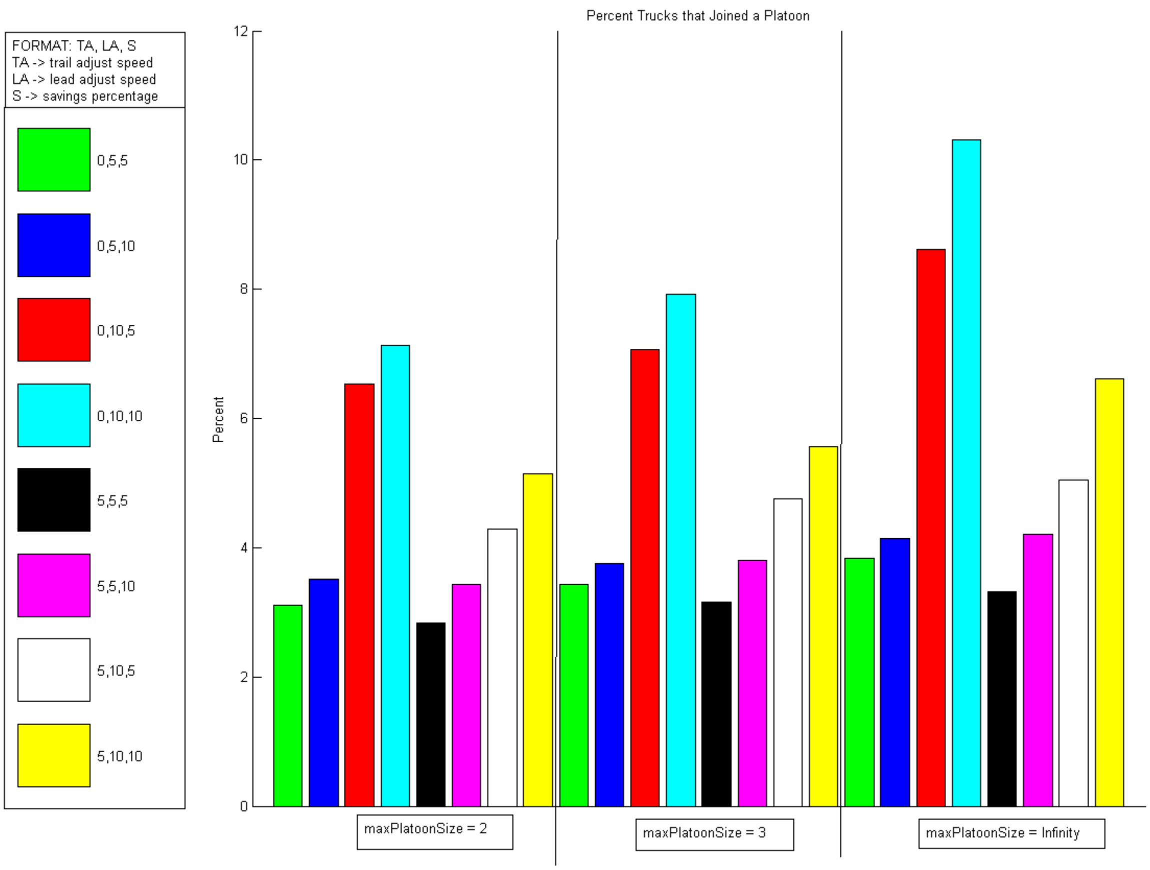


*Figure 24: NDFT1 consists of 330 platoon eligible trucks on a daily average*

*Figure 24* shows that dataset NDFT1 forms platoons with approximately 5% of the truck population. Interestingly, increasing the trail truck adjustment speed (i.e., allowing the trailing truck to accelerate more) appears to actually decrease the number of trucks that form platoons. This behavior is exhibited if the cost of acceleration exceeds the benefits of platooning. In the case of the NDFT1 dataset, in which the truck density is relatively low, we find that the distance required by a trailing truck to reach a leading truck is large. The results for dataset NDFT2, as summarized in *Figure 25*, indicate similar behavior, although the percentage of trucks in a platoon is higher when more trucks are present on the roadway.

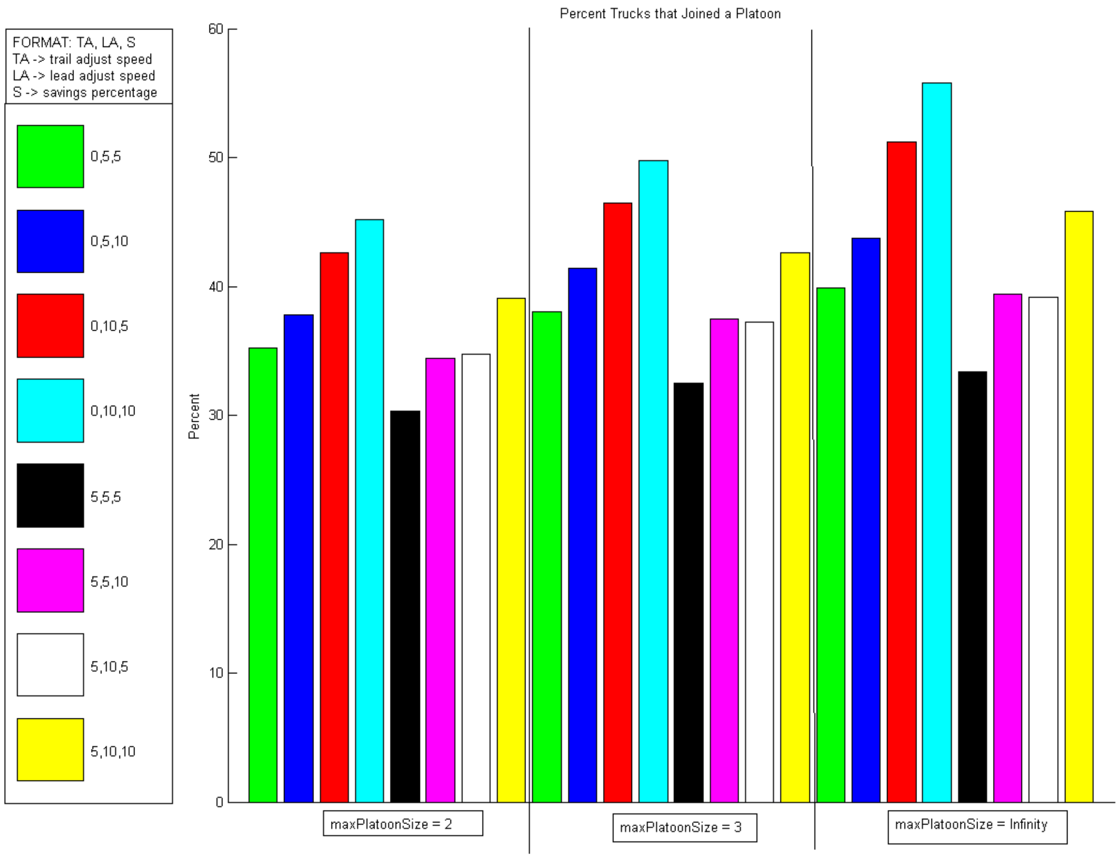


*Figure 25: NDFT2 consists of 546 platoon eligible trucks on a daily average*

*Figure 25* shows that dataset NDFT2 forms platoons with approximately 40% of the truck population. Again, increasing values of the lead truck adjustment speed (i.e., allowing the lead truck to slow down more), increasing the fuel savings parameter, and increasing the maximum allowable platoon size all appear to increase the number of trucks that form platoons. Conversely, increasing the trail truck adjustment speed (i.e., allowing the trailing truck to accelerate more) appear to decrease the number of trucks that form platoons. *Figure 37* shows that increasing the trail truck adjustment speed can increase the distance traveled in the platoon for a truck by about 20 miles. Assuming that the extra distance traveled is 20 miles, using Equations 1 and 2 and some simple distance equations, and assuming that the percent reduction in fuel cost for a platoon is 10%, the speed traveled in platoon is 63 mph, the normal lead truck speed is 63 mph, the normal trail truck speed is 65 mph, the trail truck adjustment speed is 5 mph, and the start distance between the trucks is 5 miles, then the extra energy expenditure required to form the platoon is nearly three-times as great as the energy savings from platooning.. However, if all the assumptions above are the same except that the start distance between the trucks is 1 mile, then the benefits of platooning are nearly double the extra energy expenditure required to form the platoon. This demonstrates how certain conditions, such as starting distance between the trucks, may determine whether speeding up is beneficial.

## e. Number of Platoons Formed

*Figure 26* and *Figure 27* show that the number of platoons formed decreases as the maximum platoon size allowed increases. Recall from *Figure 24* and *Figure 25* that the number of trucks that join a platoon increases as the maximum platoon size allowed increases. These trends combined mean that as the maximum platoon size allowed increases, the number of trucks that join a platoon increases, and the trucks form platoons of larger size which leads to less platoons. In other words, larger allowable platoon sizes tend to absorb smaller platoons into a single aggregate platoon.

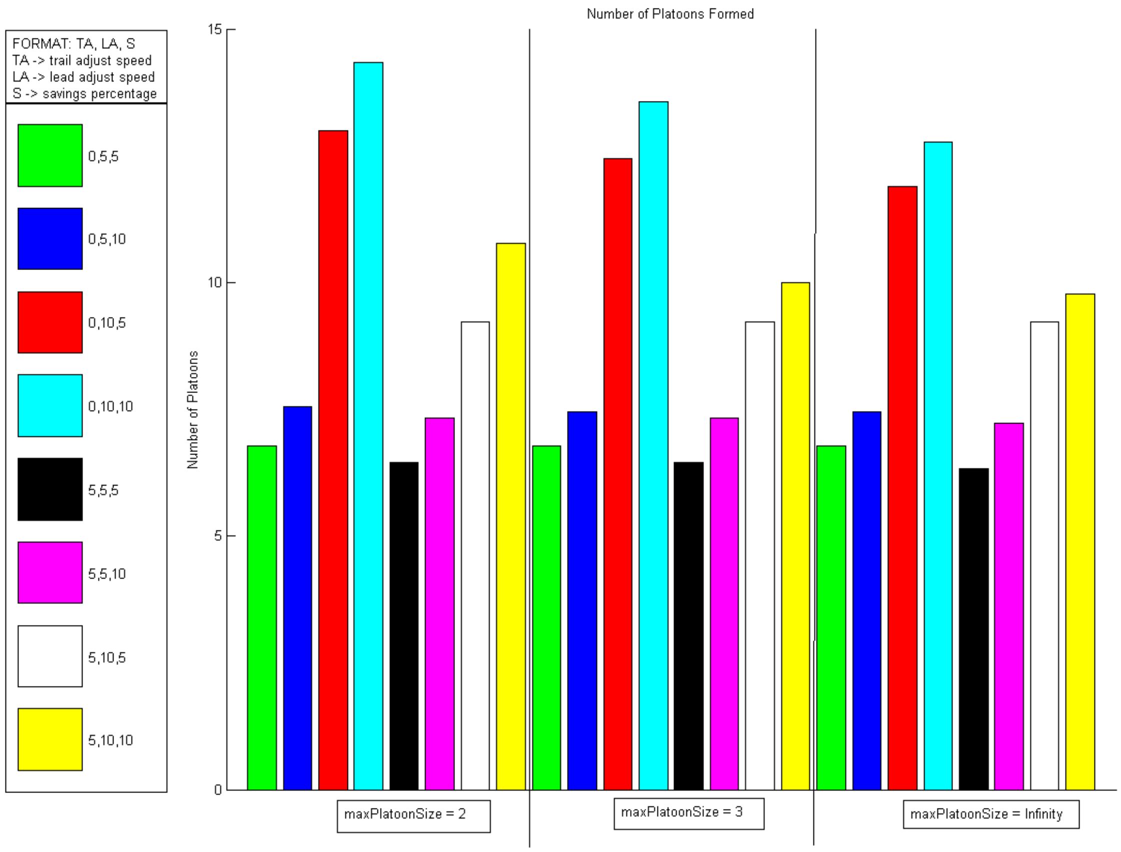


*Figure 26: NDFT1 number of platoons formed*

Increasing values of the lead adjustment speed and fuel reduction parameters seem to increase the number of platoons formed, while larger allowable platoon sizes decrease the number of platoons formed. The trail truck adjustment speed seems to have no impact when the lead truck adjustment speed is five; however, a trail truck adjustment speed of zero combined with a lead truck adjustment speed of ten results in a large number of platoons formed.

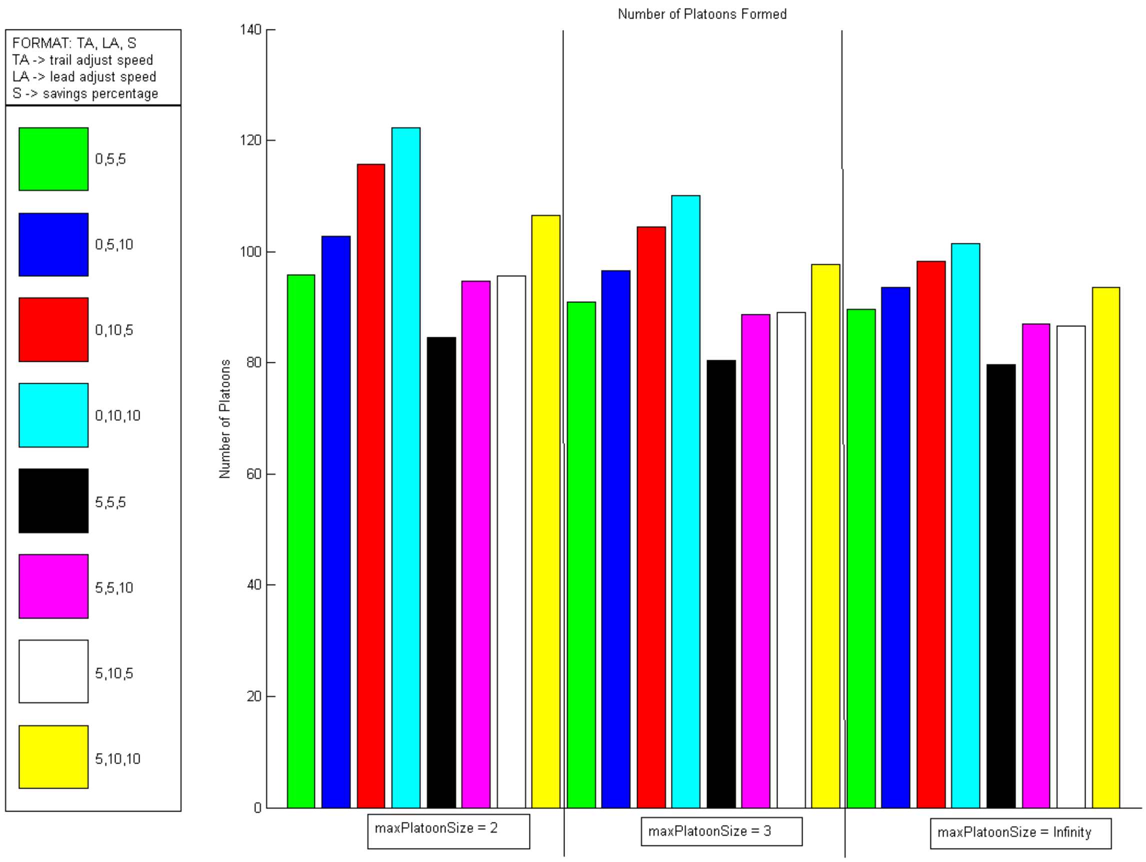


*Figure 27: NDFT2 number of platoons formed*

*Figure 27* shows an even more impressive difference in number of platoons formed than *Figure 26* when comparing parameters. In this case, a trail truck adjustment speed of zero forms more platoons than a trail truck adjustment speed of five.

## f. Number of Trucks that Lost Time

*Figure 28* and *Figure 29* show the number of trucks that experience a time delay. Both lead trucks and trail trucks can experience a time delay. For example, a lead truck may be delayed by slowing down to join a platoon. A trailing truck may be delayed if it joins a platoon in which the lead truck is traveling at a slower average speed. For the purposes of this analysis, the speed of the platoon is determined by the minimum average speed that was recorded for any of the trucks within the platoon (ignoring any temporary acceleration or deceleration required to form the platoon). For example, if the trailing truck would normally travel at 68 mph (based on the average speed calculated from the ATRI data records for this truck), but the lead truck has an average speed of 65 mph, the trailing truck would be delayed.

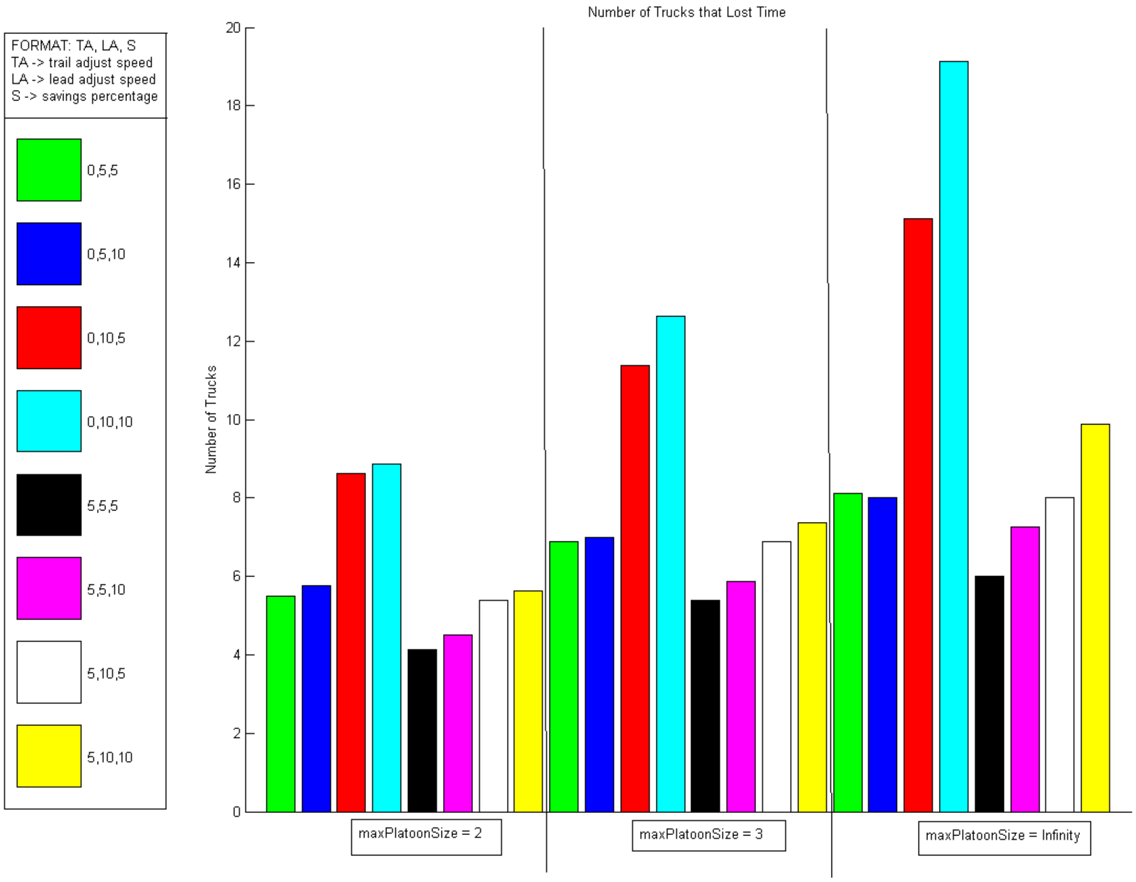


*Figure 28: NDFT1 number of trucks that lost time*

Increasing values of maximum allowable platoon size, lead truck adjustment speed, and percent fuel reduction parameters result in a larger number of trucks that lose time. In contrast, decreasing values of the trail truck adjustment speed results in more delay. This is intuitive since a larger catch-up speed reduces the amount of time a lead truck needs to travel at its decelerated speed.

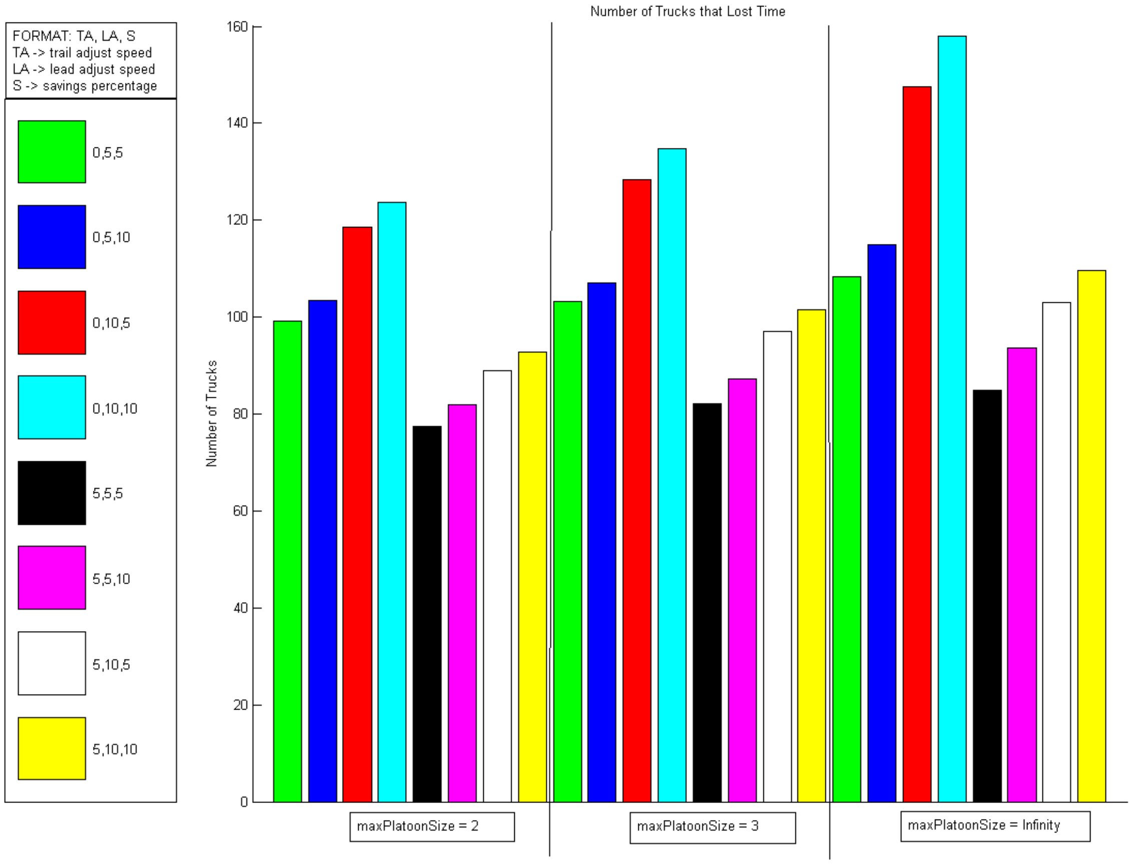


*Figure 29: NDFT2 number of trucks that lost time*

The same comments can be made for *Figure 29* as were made for *Figure 28*. Namely, decreasing values of trailing truck adjustment speed, and increasing values of all other parameters result in more trucks that lose time. The large amount of trucks losing time seems to indicate that lost time will play a role in future trucking logistics with platooning considerations.

## g. Number of Join Operations

A join operation is simply the act of adjusting speed to join a platoon. The number of joins correlates positively with the number of platoons formed.

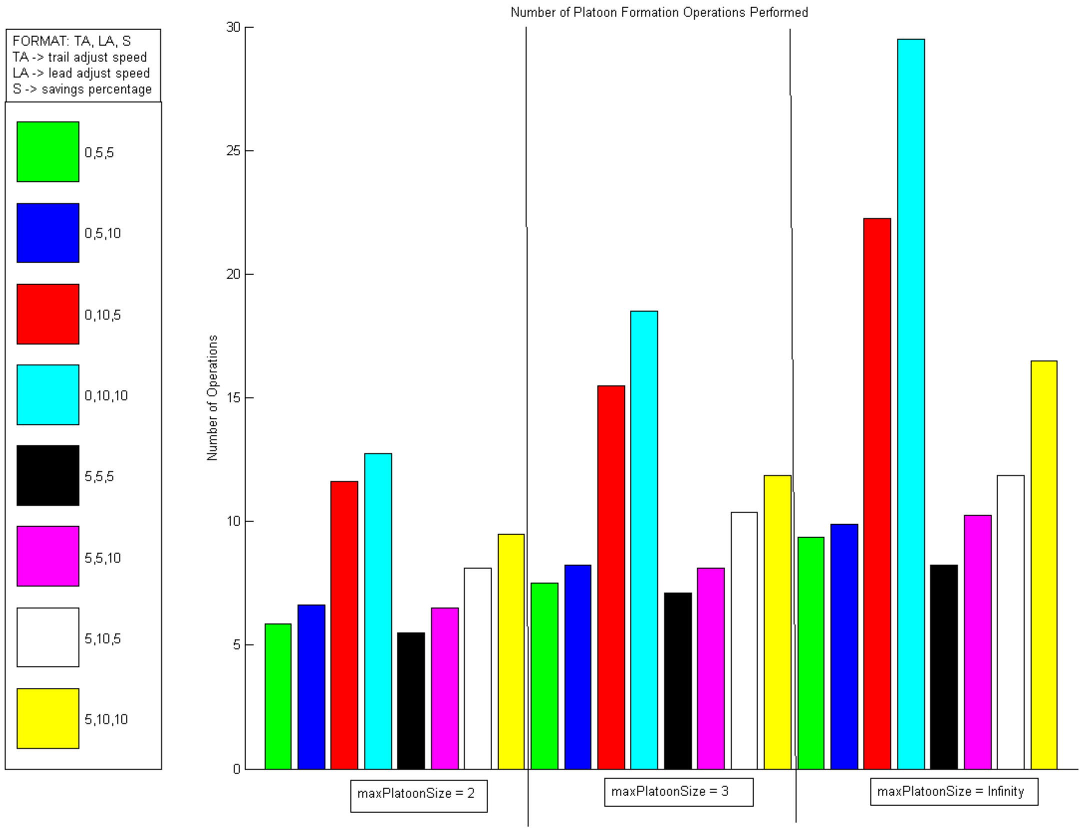


*Figure 30: NDFT1 number of join operations*

Similar to the number of platoons formed metric, increasing values of maximum allowable platoon size, lead truck adjustment speed, and percent fuel reduction, as well as decreasing values in trail truck adjustment speed result in more join operations.

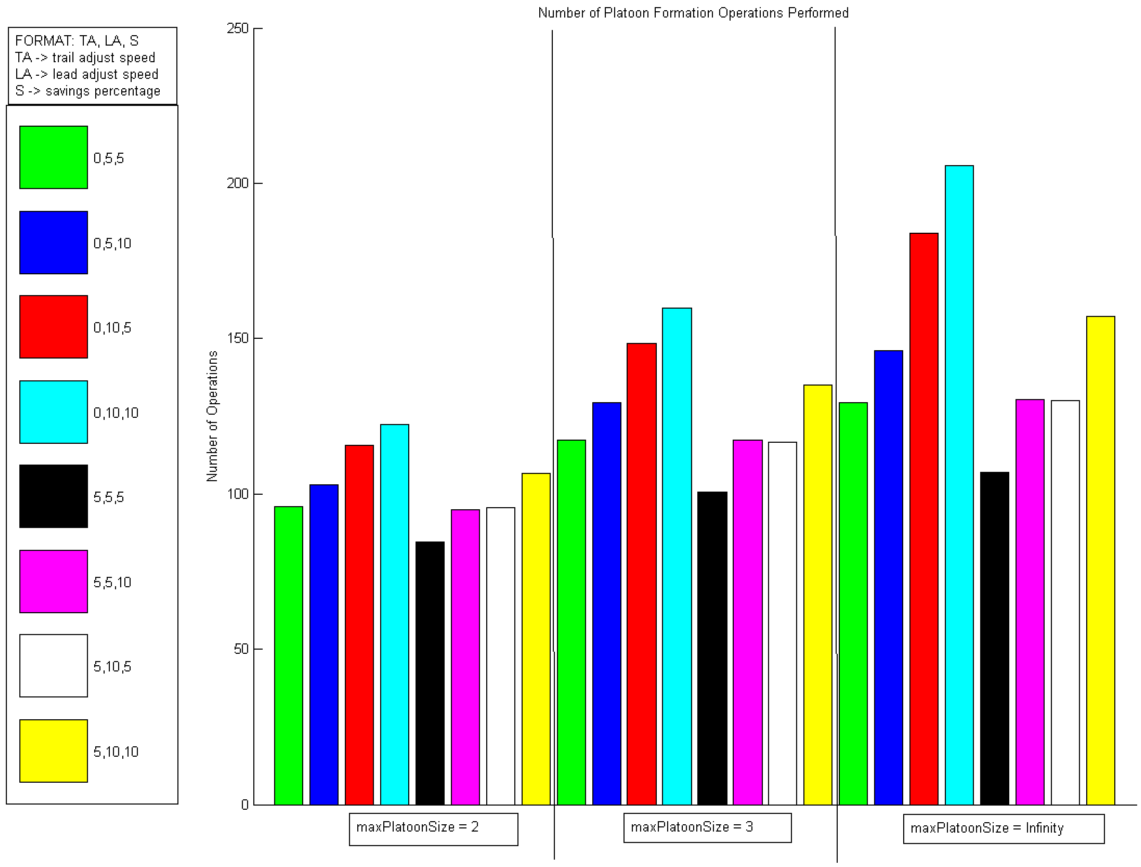


*Figure 31: NDFT2 number of join operations*

Similar to *Figure 30*, *Figure 31* shows that increasing values of maximum allowable platoon size, lead truck adjustment speed, and percent fuel reduction, as well as decreasing values in trail truck adjustment speed result in more join operations.

## h. Maximum Platoon Size at any given Time

The maximum platoon size at any given time describes the largest observed platoon size. Recall that all bars in the bar graph are averages. *Figure 32* and *Figure 33* show a correspondence with the saturation of trucks in this dataset. For instance, we see in *Figure 32* that even when permitted to form three trucks, they are unable to do so in some cases. However, in *Figure 33* we see that the maximum platoon size was reached every day when the maximum platoon size was three.

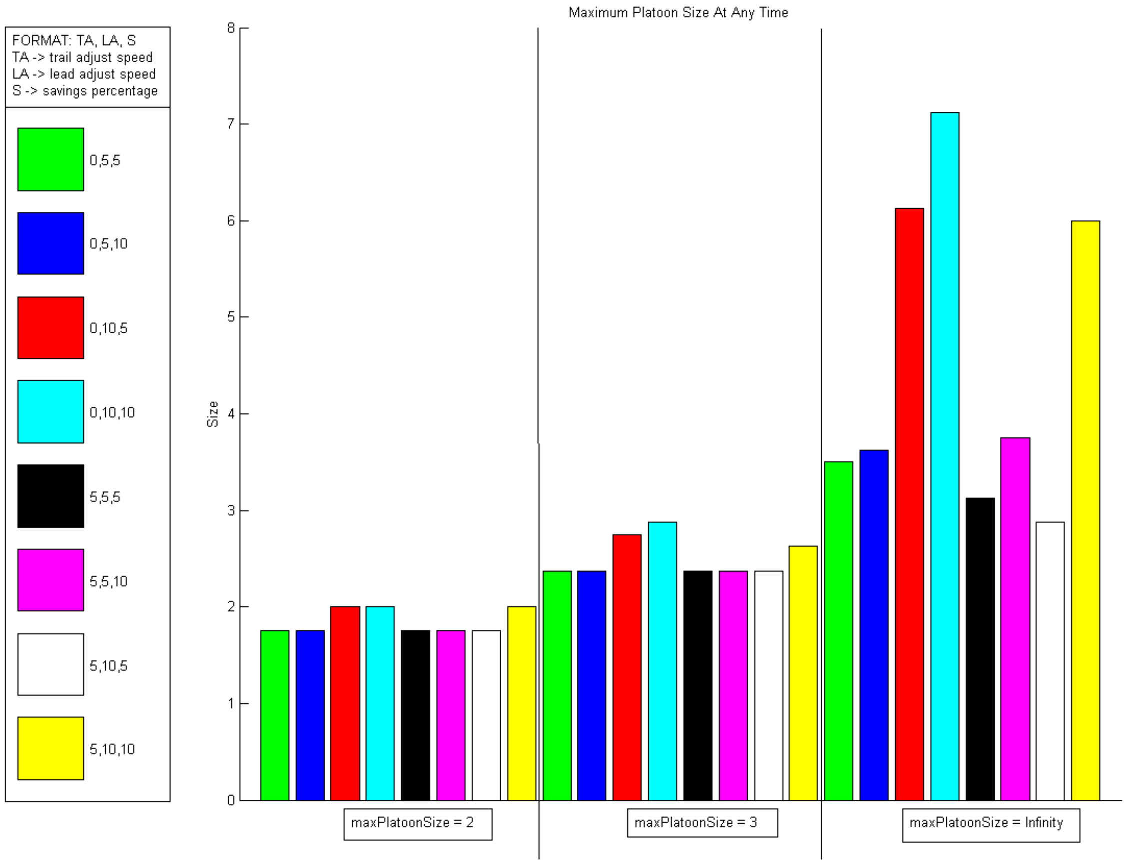


*Figure 32: NDFT1 maximum platoon size at any given time*

In the case that the maximum allowable platoon size is unrestricted, the increasing values of the lead truck adjustment speed and percent fuel reduction appear to increase the maximum platoon size observed. The trail truck adjustment speed appears to have little impact.

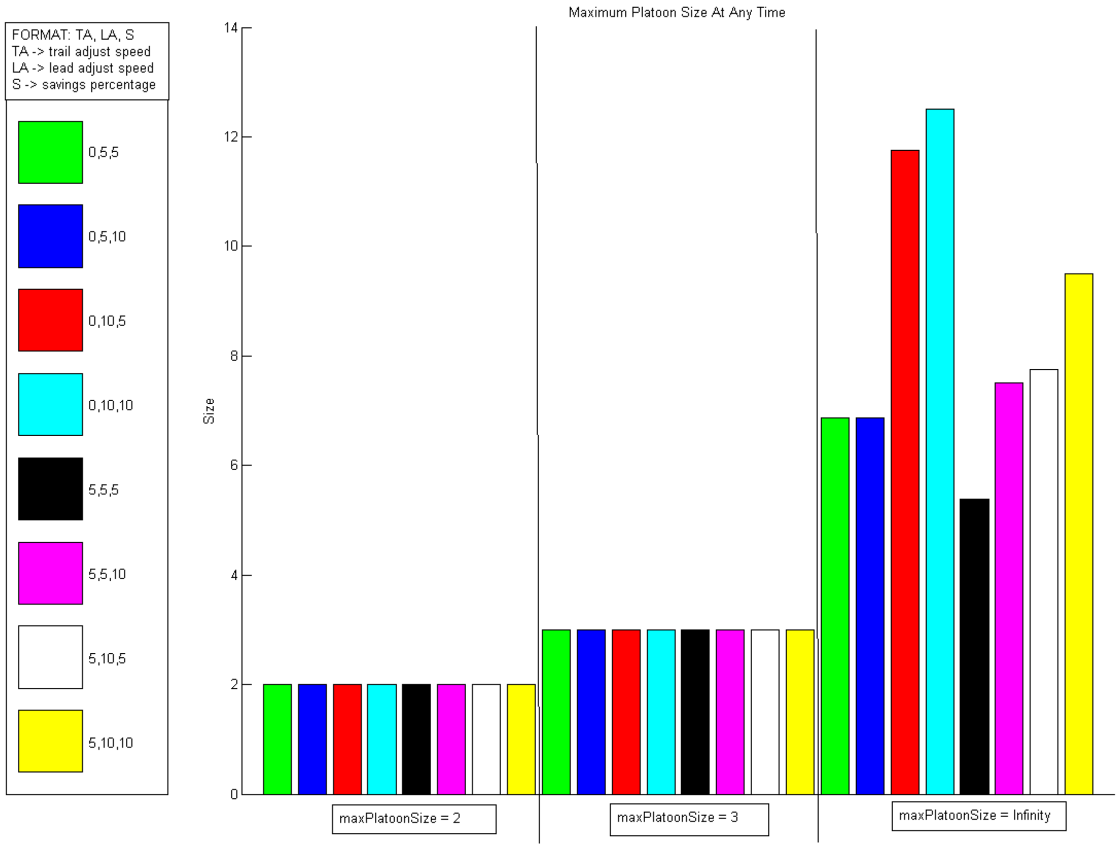


*Figure 33: NDFT2 maximum platoon size at any given time*

In the case that the maximum allowable platoon size is unrestricted, increasing the lead truck adjustment speed seems to increase the maximum observed platoon size. Both the percent fuel reduction and trail truck adjustment speed parameters seem to have little impact.

## i. Time Lost for Trucks that Platoon

Box plots (often called "box and whisker plots") are used below to depict the variability in metric values. In these box plots, the red line within each box describes the median value, the edges of the box are the $25^{th}$ and $75^{th}$ percentiles, the black whiskers are the extreme values, and the individual red crosses are statistical outliers.

The time lost metric describes how much time, in hours, individual trucks were delayed due to platooning. Overall, the lead truck adjustment speed appears to have the largest impact on time lost, which is intuitive.

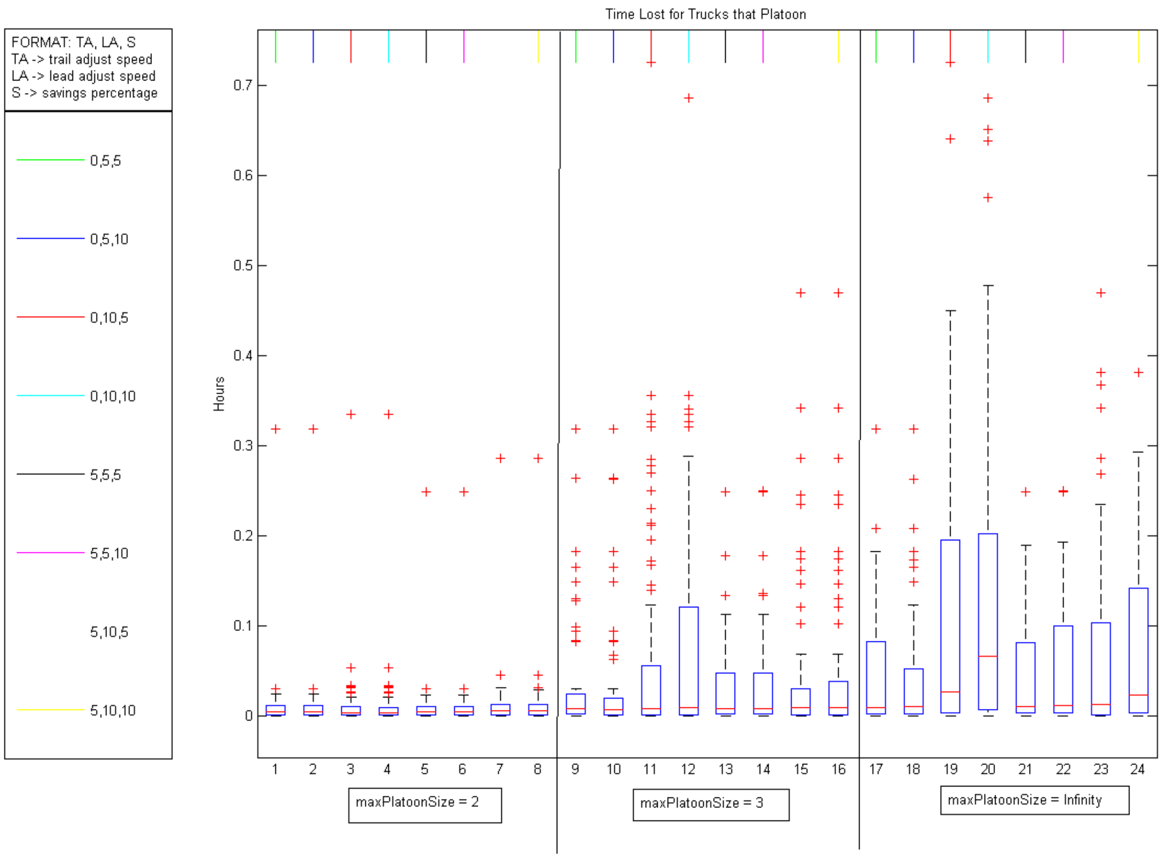


*Figure 34: NDFT1 time lost for trucks that platoon*

Increasing values of maximum allowable platoon size and lead truck adjustment speed seem to result in more time lost. The trail truck adjustment speed and fuel reduction parameter appear to have little impact.

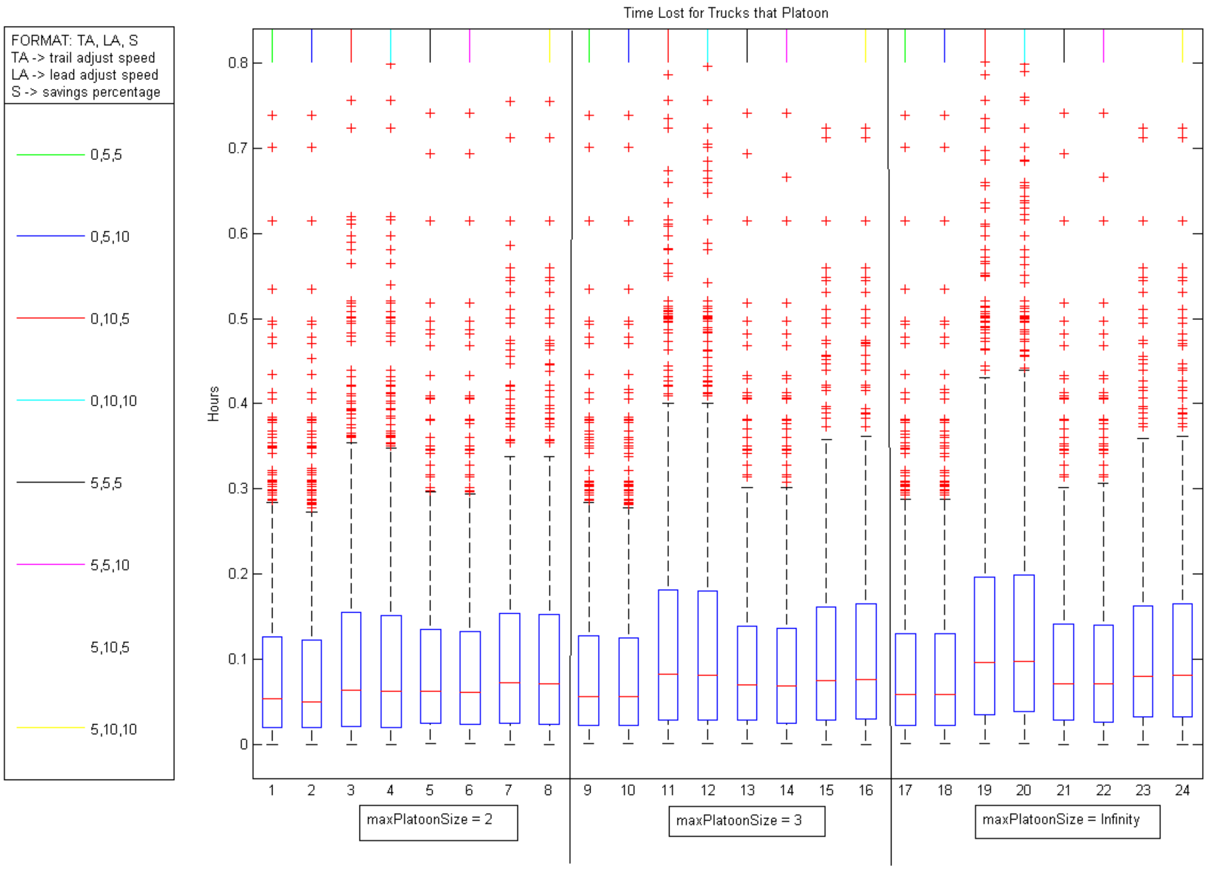


*Figure 35: NDFT2 time lost for trucks that platoon*

The only parameter value that appears to have an impact on time lost is the lead truck adjustment speed. In particular, larger values of the lead truck adjustment speed result in more time lost. This is intuitive because more deceleration is directly related to time delay. Outliers are identified by determining whether a value is greater than q3 + w(q3 - q1) or less than q1 - w(q3 - q1), where q1 and q3 are the 25th and 75th percentiles, respectively, and where w is 1.5 by default. Each NDFT2 box plot represents hundreds of observations since each day of data represents 300 to 400 platoon-eligible trucks. Eight days of trucking traffic were analyzed.

## j. Distance Traveled in Platoon by Individual Trucks

This metric shows how far individual trucks travel in platoon. *Figure 36* and *Figure 37* actually reveal even more information about the road saturation. Specifically, *Figure 36* shows the average distance that trucks travel in platoons, based on the NDFT1 dataset, while *Figure 37* shows the same metric for the NDFT2 dataset (characterized by a higher saturation of trucks). Note that the average distance traveled by trucks while in a platoon is much longer for the higher saturation situation (*Figure 37*). The data suggest that there are more platooning opportunities within dataset NDFT2 because there are more trucks, the trucks are closer together, and the truck exits are farther away from the point of formation.

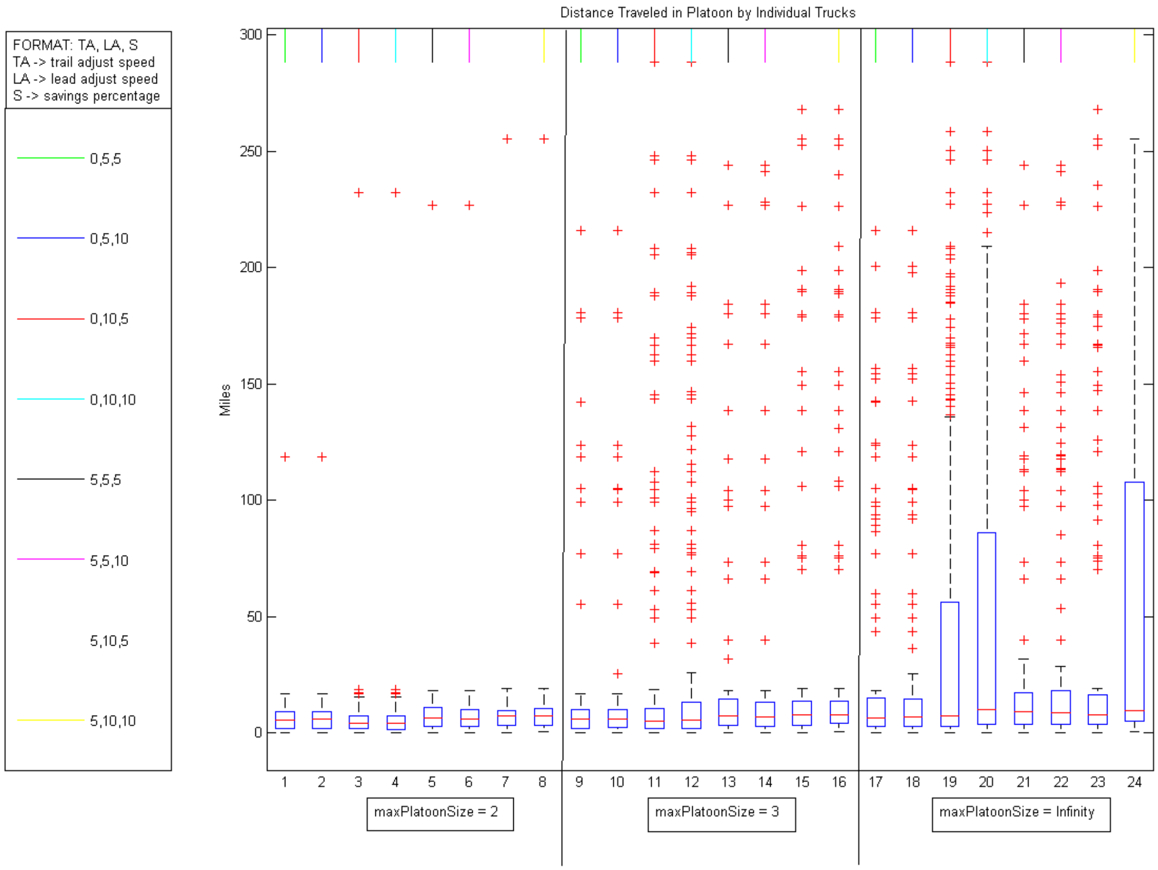


*Figure 36: NDFT1 distance traveled in platoon by individual trucks*

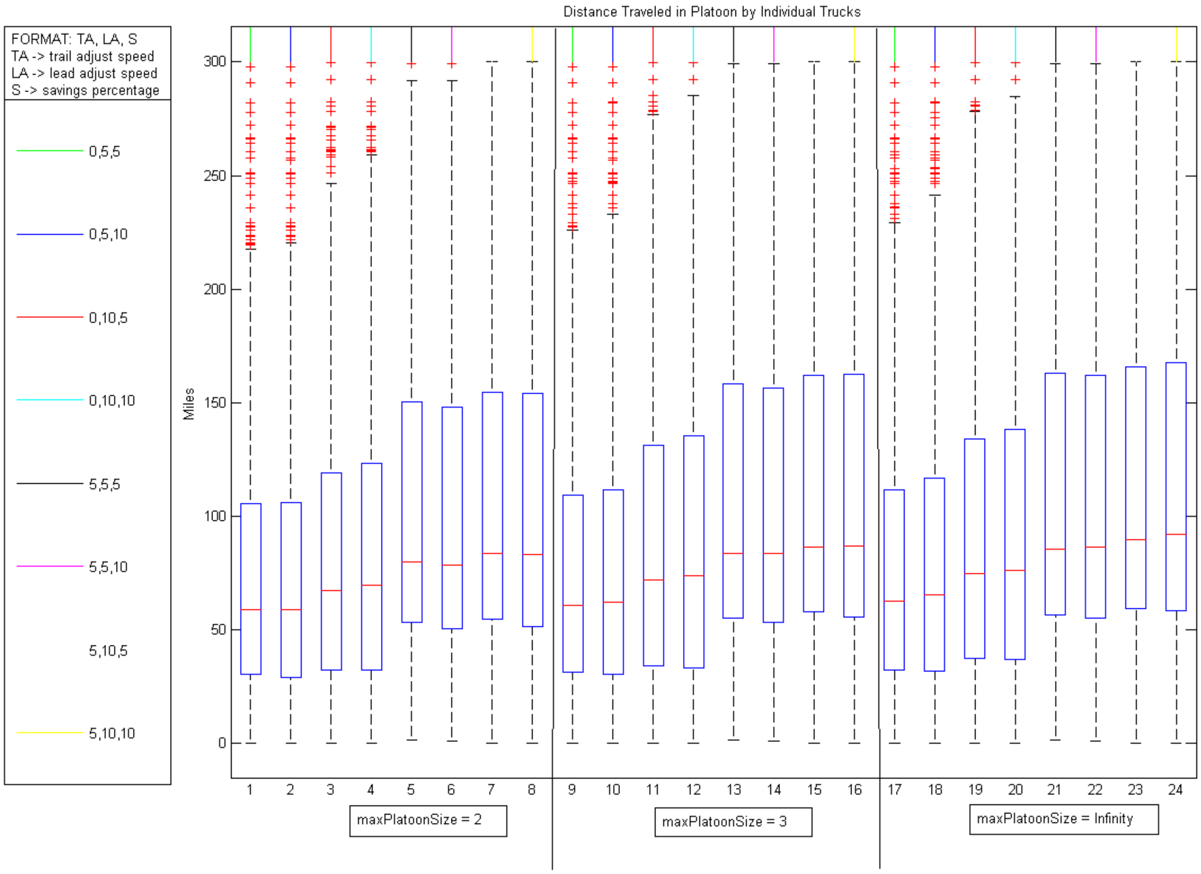


*Figure 37: NDFT2 distance traveled in platoon by individual trucks*

The most impactful parameter is the trail truck adjustment speed. In particular, increasing values of the trail truck adjustment speed increase the distance traveled in platoon by individual trucks. Also, increasing values of the lead truck adjustment speed seem to have a small impact on the distance traveled in platoon by individual trucks. The maximum allowable platoon size and percent fuel reduction appear to have no impact.

## k. Percent Distance in Platoon or Traveling Alone

*Figure 38* and *Figure 39* show, for a given truck, the percent distance traveled in platoon over the entire distance that the truck travels. For instance, if a truck travels in platoon for 80 miles on the road, and also travels for 20 additional miles on the road without being in a platoon, then the metric would be 80 percent. Note that the percentage is not respective to the length of the road, but it is respective to how far the truck travels on the road. There is a tendency for trucks to travel in platoon for a high percentage, particularly on a more saturated road. A high percentage is necessary to make up for the fuel acceleration cost.

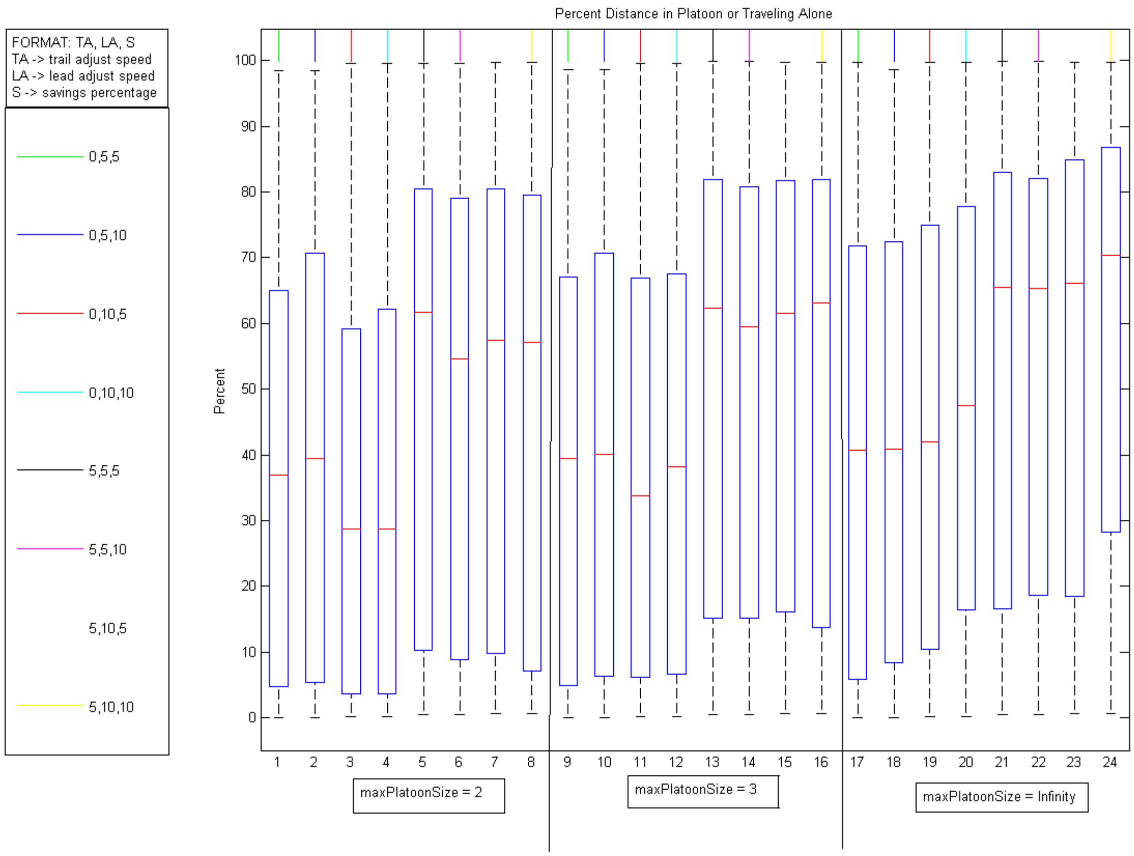


*Figure 38: NDFT1 percent distance in platoon or traveling alone*

The trail truck adjustment speed appears to have the largest impact on the results. In particular, increasing values of the trail truck adjustment speed increase the percent of the road traveled in platoon. All other parameters appear to have no impact.

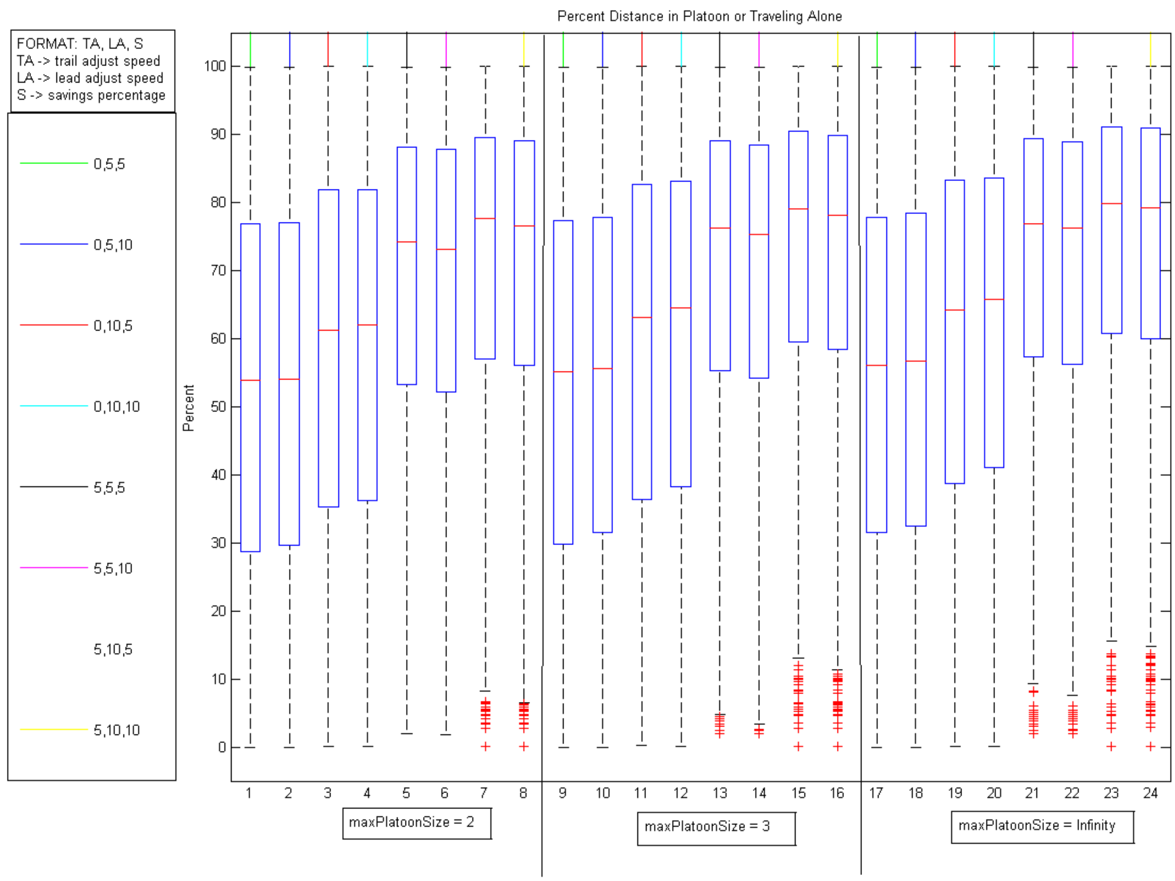


*Figure 39: NDFT2 percent distance in platoon or traveling alone*

Increasing values of the trail truck adjustment speed and the lead truck adjustment speed increase the percent distance traveled in platoon. The trail truck adjustment speed is more impactful than the lead truck adjustment speed. The maximum allowable platoon size and the percent fuel reduction appear to have no impact.

## l. Savings Earned by Trucks that Join a Platoon

The percent savings earned offers the most surprising result; namely, the savings is only sensitive to the fuel reduction parameter and the road saturation. The maximum allowable platoon size, and the adjustment speed parameters appear to have no impact on savings. The savings is higher when the percent fuel reduction and road saturation are larger. The median savings for NDFT1 is approximately 4%-6%. The median savings for NDFT2 is approximately 5%-7%.

Note that the savings calculated here is neither a dollar metric, nor a volume metric such as gallons. To obtain the percentages, we implement the approaches of Larson et al. (2013) and Liang (2014) to calculate the additional energy required to accelerate a truck, or the energy saved via drafting. This allows us to obtain a percentage on how much fuel energy savings a given truck earns. In particular, we calculate one minus the quotient of the fuel energy expense incurred in the event of platooning over the fuel energy expense incurred without any platooning or speed adjustments.

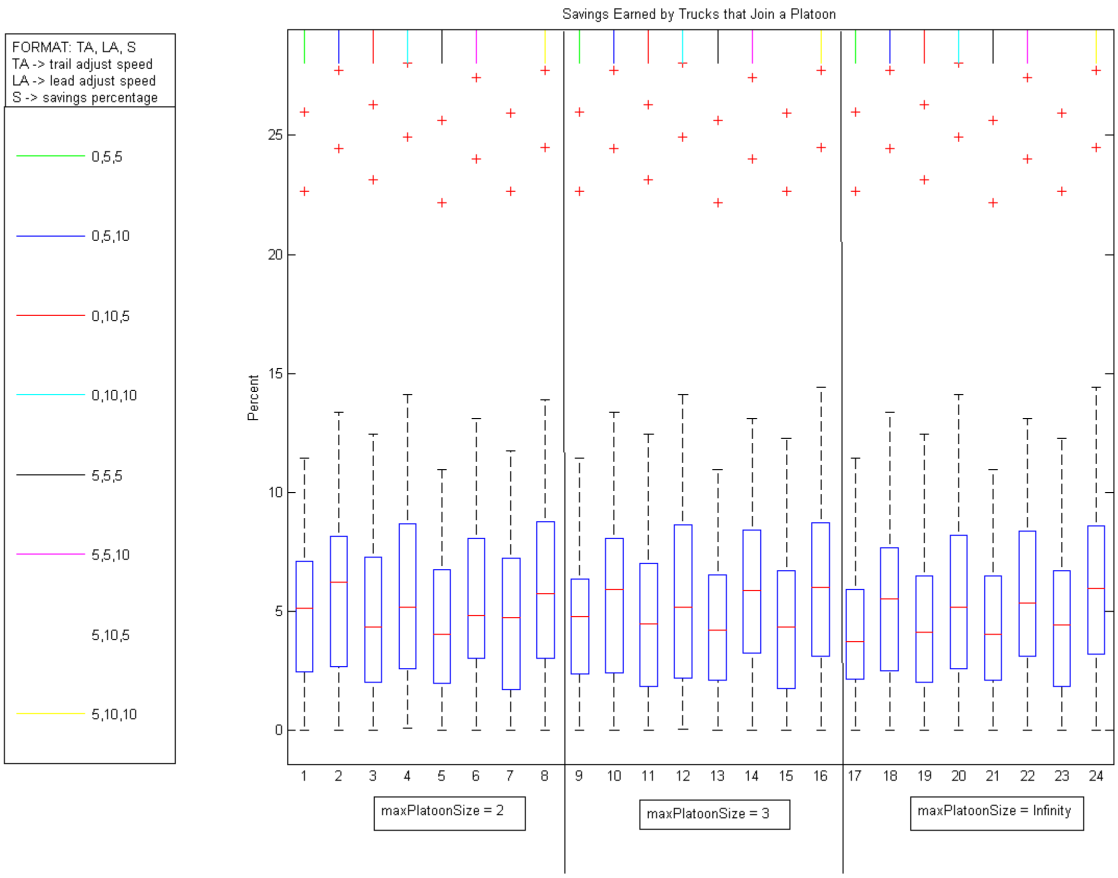


*Figure 40: Savings earned by trucks that join a platoon. Increases in percent fuel reduction and road saturation result in greater savings.*

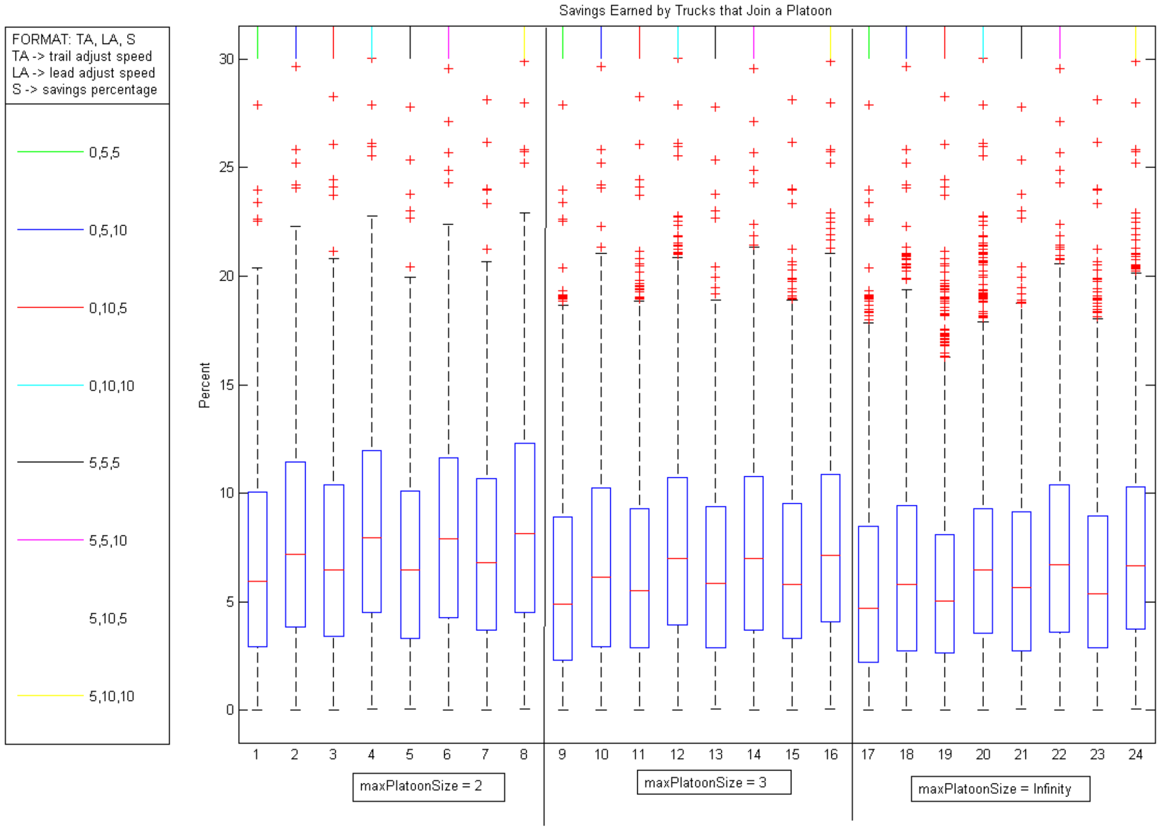


*Figure 41: NDFT2 savings earned by trucks that join a platoon. Increases in percent fuel reduction and road saturation result in greater savings.*

## m. Conclusion and Future Work

This analysis confirmed intuition about trends and how parameter values influence results. It also provided interesting metrics, such as the percent of trucks that joined a platoon in sparse road environments (maximum 10%) versus well-populated road environments (maximum 55%). A key result is that percent savings seems to only be influenced by percent fuel reduction and road saturation.

In the future, it may be necessary to constrain the time lost to a reasonable limit. Also, plans are to extend the analysis of the ATRI-provided truck data for additional highway corridors. Interstate-94 runs through a rural area, and we anticipate that urban corridors will present much higher road saturation. Another goal is to continue refining and improving the optimization algorithm. In particular, the algorithm will be even faster than its current state, and will automatically generate figures/graphs. It will be interesting to consolidate the time lost figure with the percent distance in platoon figure to identify which trucks have high time lost when traveling long or short distances. Finally, using data visualization tools, the areas where significant platooning opportunities exist will be distinguished.

Importantly, next phase work will incorporate differences in fuel economy benefits depending on platoon position. Therefore the results presented here should be considered preliminary.

# IX. *Potential Traffic Flow and Mobility Impacts*

## a. Literature Review

Cooperative Adaptive Cruise Control (CACC) is an emerging technology in Transportation Engineering. The use of CACC could potentially double highway capacity at high market penetration through the reduction of gaps between vehicles (Arem, 2006). The impact on traffic flow will be directly related to the car following guidelines that are set, specifically the admissible time gap between vehicles (Shladover, 2012). Closely spaced platoons should lead to significant savings in fuel cost (Zhang, 2014).

Throughout the literature on this subject there are many different techniques for setting the guidelines of following behavior. In practice, the vehicle industry will set following behavior as they design specific products. At this point there are no design standards on how to operate CACC (Arnaout, 2014); it is an open question as to whether such design standards are needed.

This literature review describes the general effects of CACC technology on traffic conditions, including its advent from the older adaptive cruise control. It discusses the reliability, safety, and feasibility of the technology. It will also discuss CACC's effect on traffic flow, and techniques for simulating the effects of the technology on roadways.

### i. Reliability/Safety/Feasibility

Riemann looked at the parameter sensitivity of CACC as represented in a microscopic traffic simulation model and how the 'time to collision' changes when these parameters are varied. The model was simulated in VISSIM using a C++ script to model the vehicle communication (VCOM) set up for CACC. There were three separate driver behaviors considered in the simulation that were all determined from a driving simulator study conducted at the Interdisciplinary Centre for Transportation Science (Riemann, 2012). The simulation focuses on a vehicle breaking down on the A5 motorway in Germany. The parameters varied in the study are the equipment rate on the roadway, and the communication range of the CACC technology. The results of the simulation show when the communication range of the technology is held constant at 300 meters, the time to collision is only significantly lower than the 0% market penetration at the 80% market penetration level. The communication ranges of 300 meters and 500 meters are both significantly different from a baseline of 100 meters at any CACC penetration over 40% (Riemann, 2012).

### ii. Effect on Traffic Flow

#### All vehicles

CACC is primarily designed for driver comfort/convenience, safety, and efficiency (Arem, 2006). The leading vehicle in a platoon dictates the action sequence, or how these vehicles will move through the roadway (Zhao, 2013). CACC technology operation goes through three progressions: forming, gap adjusting, and platoon steadying (Zhao, 2013). The convention throughout literature has been to use a 0.5 second time gap for CACC following to keep string stable behavior. String stable behavior refers to the information moving through multiple controllers; with CACC the number of controllers and information can lead to complex non-stable behavior. The following time for manual vehicles in the literature varies from 1.2-1.5s.

A simulation was completed using the microsimulation tool MIXIC; of a four lane roadway dropping a lane to measure changes in shockwaves (Arem, 2006). The results of the simulation showed no significant difference in traffic flow when market penetration of CACC is less than 40%. CACC made lane change failures more evident; it was noted that the cooperative merging procedure needs to be investigated

(Arem, 2006). Stability of the traffic improved without an increase in capacity; this could be due to the roadway in the simulation already having a traffic volume approaching capacity (Arem, 2006).

Kesting theorized that a twenty-five percent penetration of CACC would eliminate congestion in a prior study. Also, a five percent penetration would show noticeable improvement in traffic flow (Shladover, 2012). Based on this a simulation took place focused on 6.5 km section of a single lane freeway. There are four different types of vehicles included: manual, ACC, 'here I am' (non-ACC vehicles that broadcast location and speed), and CACC. The study varied the penetration levels for both ACC, and CACC through multiple trial simulations. The results showed ACC to have little impact on increasing the baseline (manual) lane capacity which was 2200 vehicles per hour (Shladover, 2012). The simulation shows at 100% penetration of CACC the lane capacity can increase up to 4000 veh/h (Shladover, 2012). If vehicles that do not have CACC technology are equipped with 'Here I am' (HIA) they can be the leading car in a platoon (Shladover, 2012). At a 20% market penetration of CACC, HIA can increase the capacity of a roadway 7% (Shladover, 2012). The impact of HIA is heightened at greater CACC market penetrations; at 60% CACC, the capacity increases by 15%.

Another simulation framework focused on traffic flow stability (Schakel, 2010). The simulation is completed on a 4.0 kilometer section of a single lane road. The traffic begins moving at 90 kilometers per hour, for 80 seconds, then decelerating to 36 km/h, at this point they then accelerate back to 90 km/h. This study simulated a shockwave in the traffic flow. This simulation looked at CACC penetration levels of 0, 50, and 100 percent. The results showed CACC will increase the initial deceleration of a shockwave, this will shorten the duration and increase the range (Schakel, 2010). The shockwave speed could pose issue to human drivers on the roadway (Schakel, 2010). This is due to the speed with which the shockwave moves through the system. It will be necessary to include dynamic reaction time to keep the roadway collision free (Schakel, 2010).

Arnaout looked at deployment strategies for CACC technologies as prior research tends to indicate CACC technology is not beneficial under 40% penetration. A 6 km 4-lane U-shaped freeway was modeled in the F.A.S.T. simulator. F.A.S.T. is a simulator developed by Arnaout focusing on a U-shaped freeway. The simulation took place both including and without a ramp. The three cases of simulation are no CACC, 20% CACC in the HOV lane, and 20% CACC in mixed traffic. When a ramp was included, the flow rate of traffic increased in both CACC instances (Arnaout, 2014). The time spent on the roadway is the smallest for the HOV lane, though as flow of traffic increases results becomes similar in all cases (Arnaout, 2014). The highest average speed comes from the mixed traffic CACC, while the HOV case had steadier traffic flow (Arnaout, 2014). The results when a ramp is not included are as follows. The HOV case will increase the flow rate and average speed even at low penetration rates, the mixed case is not significantly different from the base (Arnaout, 2014). The use of CACC will reduce travel time but only when there is a high traffic flow (Arnaout, 2014).

### Truck Platooning

The annual costs due to delay and wasted fuel are $23 billion dollars (Zhang, 2014). In Europe, trucks are electronically limited to a top speed that naturally clusters them on highways; drivers already have a cooperative approach (Ploeg, 2011). The truck drivers can coordinate behavior at exits to let vehicles cross a platoon and exit (Ploeg, 2011). The truck industry is more homogeneous in specifications and performance parameters than the car industry, such that this can improve regulation of the CACC industry (Ploeg, 2011). Aftermarket and service channels for trucks can enable a swift introduction of CACC (Ploeg, 2011).

Experiments have shown that string stable behavior is possible with heavy duty trucks with sufficiently large headway times (Nieuwenhuijze, 2012). String stable behavior is enhanced by having the lighter truck following in the platoon (Nieuwenhuijze, 2012).

## b. Methodology

Microscopic traffic simulation in this study utilizes CORSIM, developed by the McTrans Center at the University of Florida. This software allows for the modeling of advanced technology vehicles with their own headway distribution. These advanced technology vehicles are defined to be trucks in this study, and set based on the parameters on the simulation case. The parameters that are varied include headway, traffic volume and market penetration. The headway of passenger vehicles without any advanced technology is a distribution centered on a value of 1.50 seconds. This is the normal distribution of drivers in heavy traffic and the random characteristics of individual's car following maneuvers follow the University of Pittsburgh (Pitt) car following model. This model incorporates the distance headway and speed differential between the lead and follower vehicles (Rakha, 2002). The Pitt car following model allows setting a minimum distance between lead and following vehicles regardless of speed. In the model created the Pitt car minimum following distance is set to 10 feet. This distance best approximates true roadway conditions. In the modeling cases with advanced technology vehicles present the non-advanced vehicles headway and following characteristics remain constant. The first CACC vehicle characteristic that is varied is vehicle following headway. As discussed earlier the non-advanced technology vehicles are on a distribution centered at a value of 1.50 seconds. The advanced technology vehicles use CACC following to eliminate the variability of their headway and thus are set as a single value rather than a distribution. There are four values that are investigated in this model: 1.25s, 1.00s, 0.75s, and 0.50s. These values are used to investigate how CACC technology will affect flow from currently realistic values to values that may be possible at a later time. In order to find the point where this technology becomes beneficial it is necessary to investigate market penetration. There are six values used for this parameter: 0%, 20%, 40%, 60%, 80%, and 100%. Varying market penetration can allow those that will regulate this technology to identify the optimal penetration to introduce this technology into all traffic streams.

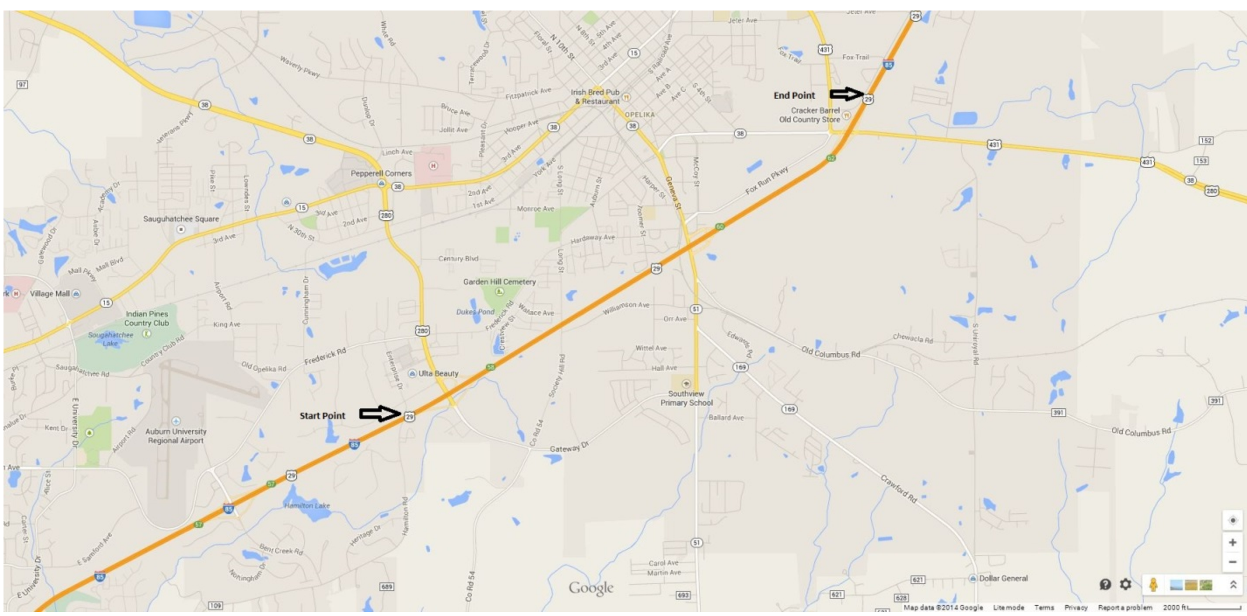


*Figure 42: Map of Simulation Area*

*Table 5: Baseline Traffic Volume Information*

| Location by Exit | AADT (vehicles/day) | Northbound Peak Hour Volume (vehicles/hour) |
|---|---|---|
| Between 57 and 58 | 39900 | 2853 |
| Between 58 and 60 | 45360 | 3243 |
| Between 60 and 62 | 45490 | 3252 |
| Between 62 and 64 | 34470 | 2465 |

In order to discuss the third parameter it is first necessary to introduce the location used for the modeling process in CORSIM. The selected section of roadway was selected for its truck volume, number of exits, and overall traffic flow. The area is shown in *Figure 42*. It is a section of Interstate 85 in the Auburn-Opelika area. This is a 5.3 mile section of I-85 northbound from just south of exit 58 to just north of exit 62. This allows the model to include three different exits. The traffic volumes were taken from the Alabama Department of Transportation's Alabama Traffic Data website. The volumes are initially given as an Average Annual Daily Traffic (AADT); this AADT is then converted into an hourly count. At this point these values are multiplied by the K factor to give the peak hour volume. This peak hour volume is multiplied by the directional (D) factor to give the peak hour traffic volume in the dominant direction of traffic. These peak hour volumes are calculated for origin point of traffic in the model which is between exits 57 and 58 on I-85, and on each subsequent on and off ramp on the roadway until after exit 62. In addition to the traffic volumes this site also gives the percentage of trucks on the roadway, and on each of the on/off ramps. The traffic volume information is shown in *Table 5*. The traffic volumes are also the third parameter that is varied in the modeling process. There are three values investigated in the modeling process: Baseline traffic volume, 115% Baseline volume, and 130% Baseline volume. Traffic volume increases were modeled to address traffic growth over time as well as scenarios in which volumes approach capacity.

After the segment was chosen for the model and the traffic volumes were calculated the initial model (representing existing conditions) was created in CORSIM. Platoons enabled by CACC-equipped vehicles were limited to two-vehicle platoons. As an example of how market penetration level affects the platooning of heavy trucks in the simulation, if a simulation run included 100 heavy trucks, 20 of them would have CACC capability, resulting in 10 two-truck platoons with the other 80 trucks not operating in platoons. The three parameters of headway, market penetration, and traffic volume were varied in according to a matrix in order to examine the effects of each. Including the baseline cases of all three traffic volumes led to sixty-three models. These simulation cases are summarized below.

- Traffic Volume: Current Conditions, 115% of Current Conditions, 130% of Current Conditions
- CACC Headway: 1.25s, 1.00s, 0.75s, 0.50s
- Market Penetration: 20%, 40%, 60%, 80%, 100%
- At this point the simulation cases were ready to be run and results to be analyzed.

## c. Results

Both the headway and market penetration of the DATP equipped trucks show significant difference from the baseline conditions at all of the traffic volumes investigated. The four levels of headway show extremely different results when holding all other factors constant. As an example, *Figure 43* and *Figure 44* show the average speed and travel delay for the vehicles on the roadway, respectively. The travel delay results correspond to the additional time (in seconds) needed for each vehicle to complete its movement through the roadway as compared to free flow conditions. The travel delay results shown are the aggregate of all the vehicles on the roadway. The results in the figures are at the current PHV and one hundred percent market penetration. The full results from all simulation cases are shown in the tables at the end of the results section.

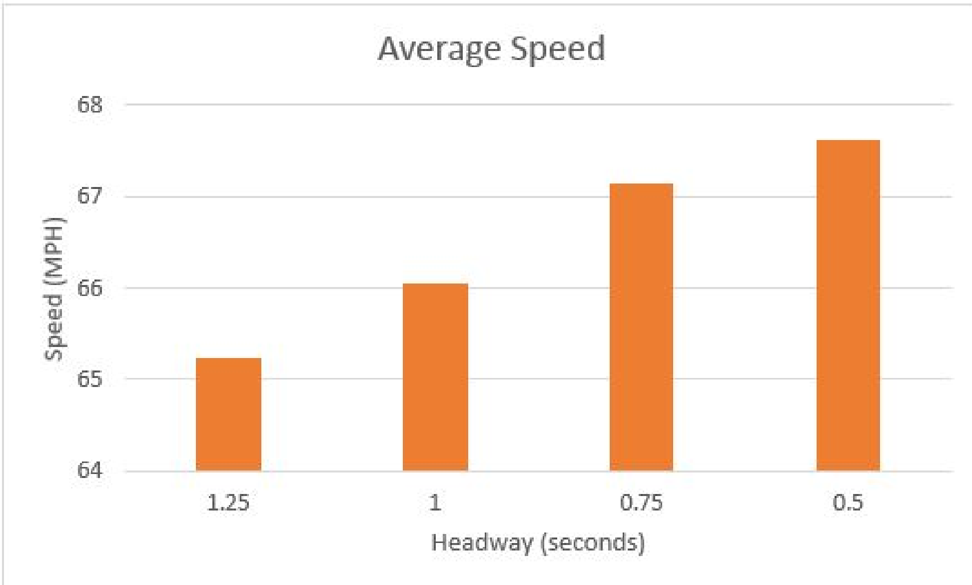


*Figure 43: Average Speed at current PHV and 100% Market Penetration*

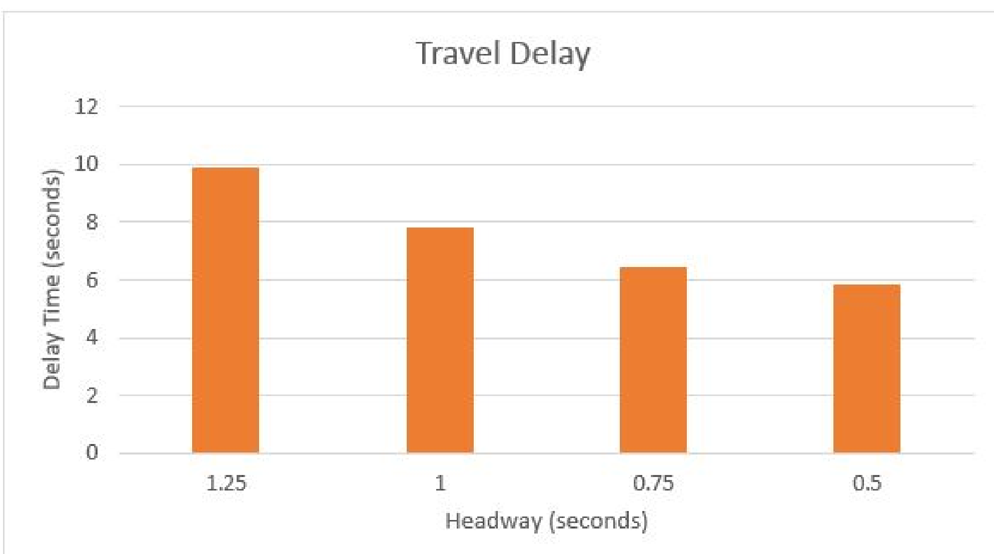


*Figure 44: Travel Delay at current PHV and 100% Market Penetration*

The non-CACC vehicles on the roadway are moving on a headway distribution centered at a value of 1.5 seconds. In all of the cases of simulation the first CACC headway examined (1.25 seconds) is not significantly different from the initial baseline. The average speed examined above shows how closing the gaps between the platoons allows for more efficient movement through the section of roadway. The increase in average speed is directly related to the decrease in delay time that is also shown above. Market penetration was also investigated using five different values. *Figures 45*, *46*, and *47* show the average speed at all the values of market penetration. These graphs include the average speed at all of the headways included in simulation to show the combined effect of these two parameters. The effect of market penetration on the average speed is shown to vary largely depending on the headway chosen. At a 20% market penetration there is no significant difference from baseline conditions regardless of the headway. The 60% penetration increases nearly linearly through the decrease in headway between vehicles. At the 100% penetration condition the increase in average speed increases at a greater rate than a linear relationship. The full results are summarized in the tables at the end of the results section.

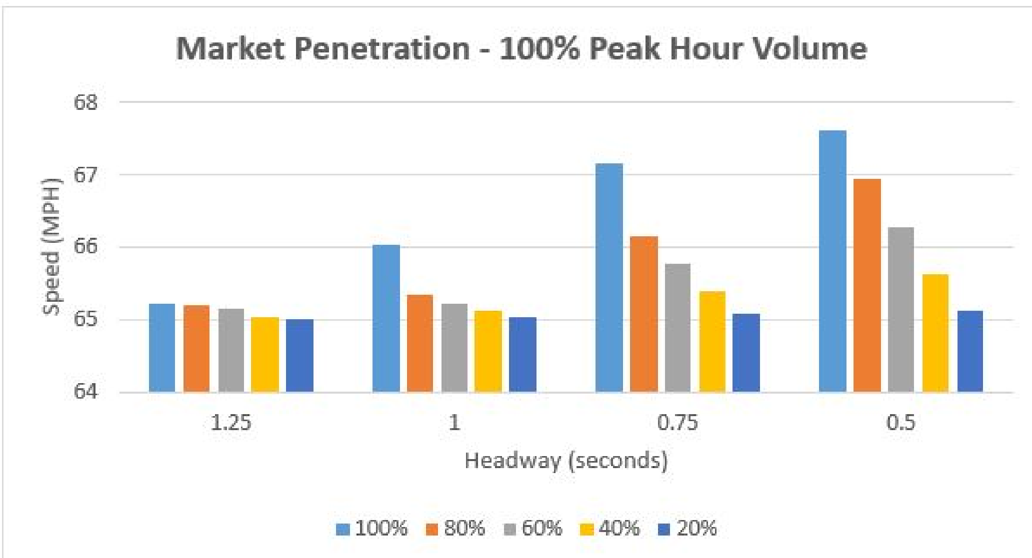


*Figure 45: Average Speed at Current PHV at all Market Penetration Values*

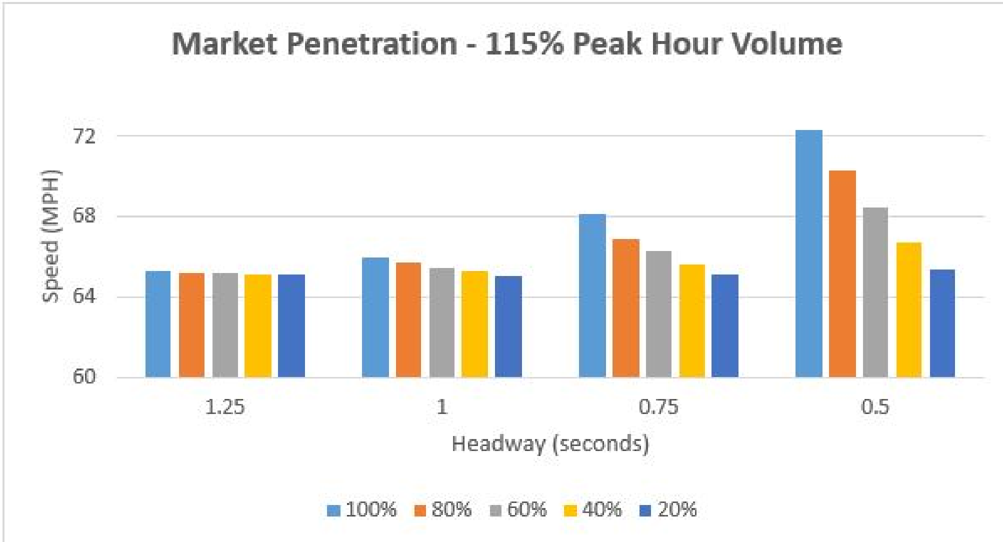


*Figure 46: Average Speed at 115% PHV at all Market Penetration Values*

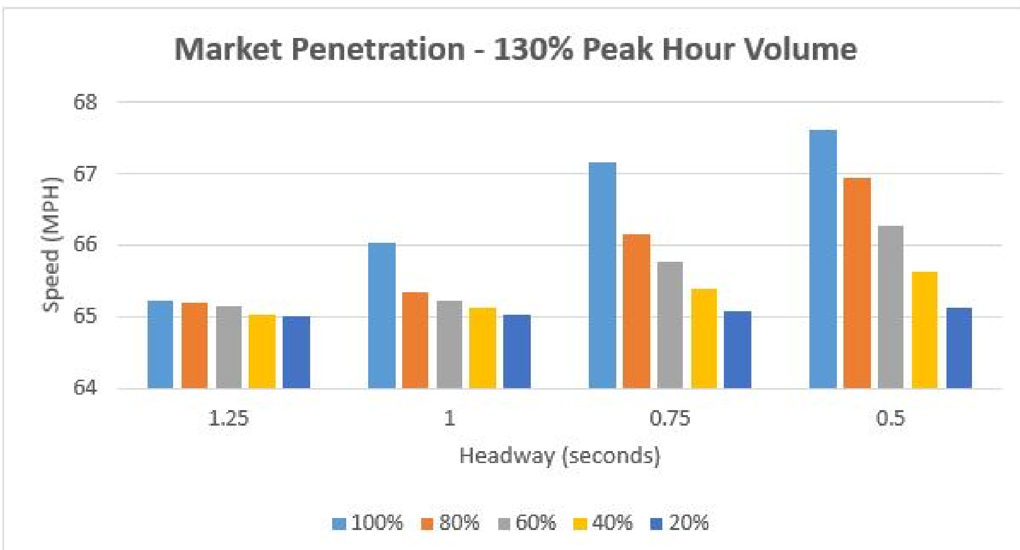


*Figure 47: Average Speed at 130% PHV at all Market Penetration Values*

*Figure 48* shows the comparison of delay time for two of the forecasted traffic volumes of the model. The current traffic volume does not see the same amount of benefit as the 130% of existing volume condition. With more traffic on the roadway there is more delay for all vehicles, and controlling the CACC headways allow for greater savings in delay. The savings for the 130% condition are much greater than the baseline at 1.00 second headway and this difference in the two decreases as the headway also decreases.

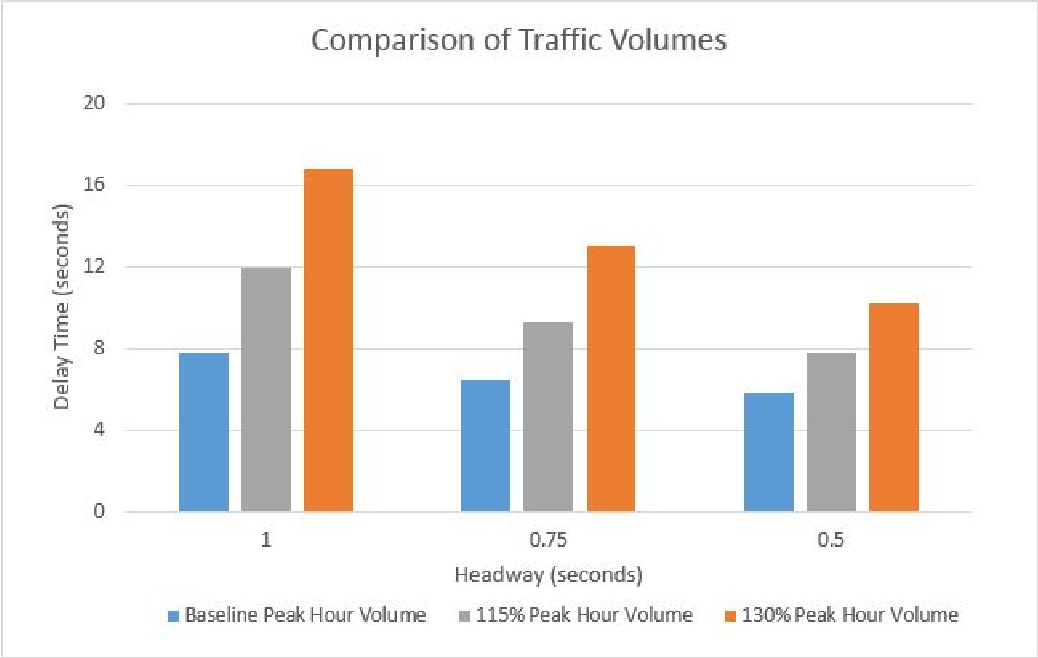


*Figure 48: Comparison of Delay at Current PHV, 115% PHV, and 130% PHV*

*Table 6: Baseline Model Results*

| Baseline Model Results | | |
|---|---|---|
| Traffic Volume | Travel Delay (sec) | Average Speed (mi/h) |
| PHV | 19.11 | 65.02 |
| 115% PHV | 46.68 | 65.11 |
| 130% PHV | 69.08 | 65.07 |

*Table 6* shows the results of the baseline simulation cases that replicate current conditions (no CACC and headway of 1.5 seconds). It is important to note that the delay reported in these tables is the aggregated increased travel time from free-flow conditions. The baseline models, reflecting current traffic conditions (100% PHV), experiences a delay from free flow of about 19.1 seconds. *The delay and average speed values in Tables 7-12 should be compared against the values in Table 6 to measure the changes brought about by DATP-equipped two-truck platoons as their respective levels of market penetration; lower values of delay and higher values of speed represent benefits for the entire traffic stream.* The delay values shown in the *Tables 7-12* represent additional travel time through the 5.3-mile study section when compared with free-flow traffic. For example, for the existing traffic volume scenarios, the reduction in travel time between 19.1 seconds (baseline condition from *Table 6*) and full market penetration of CACC among heavy trucks, assuming an average headway of 0.5 seconds per vehicle (a delay of 5.8 seconds as found in *Table 7*) would be 13.5 seconds. These results apply to the entire traffic stream and represent the travel times and speeds for the average vehicle.

*Table 7: Travel Delay Results at the Current PHV*

| **100% Peak Hour Volume - Travel Delay in seconds** | | | | | |
|---|---|---|---|---|---|
| | Market Penetration (%) | | | | |
| Headway (s) | 100% | 80% | 60% | 40% | 20% |
| 1.25 | 9.875 | 11.258 | 13.134 | 15.011 | 18.763 |
| 1 | 7.811 | 9.374 | 10.936 | 13.142 | 15.623 |
| 0.75 | 6.450 | 8.453 | 9.030 | 10.319 | 12.899 |
| 0.5 | 5.851 | 7.021 | 8.191 | 9.362 | 11.416 |

*Table 8: Average Speed Results at the Current PHV*

| **100% Peak Hour Volume - Average Speed in MPH** | | | | | |
|---|---|---|---|---|---|
| | Market Penetration (%) | | | | |
| Headway (s) | 100% | 80% | 60% | 40% | 20% |
| 1.25 | 65.230 | 65.190 | 65.140 | 65.040 | 65.010 |
| 1 | 66.042 | 65.339 | 65.226 | 65.113 | 65.023 |
| 0.75 | 67.144 | 66.152 | 65.764 | 65.380 | 65.076 |
| 0.5 | 67.612 | 66.939 | 66.280 | 65.634 | 65.126 |

*Table 9: Travel Delay Results at 115% PHV*

| **115% Peak Hour Volume - Travel Delay in seconds** | | | | | |
|---|---|---|---|---|---|
| | Market Penetration (%) | | | | |
| Headway (s) | 100% | 80% | 60% | 40% | 20% |
| 1.25 | 20.775 | 24.929 | 29.084 | 33.239 | 41.549 |
| 1 | 11.909 | 14.291 | 16.673 | 19.054 | 23.818 |
| 0.75 | 9.298 | 11.158 | 13.017 | 14.877 | 18.596 |
| 0.5 | 7.806 | 9.367 | 10.928 | 12.490 | 15.612 |

*Table 10: Average Speed Results at 115% PHV*

| **115% Peak Hour Volume - Average Speed in MPH** | | | | | |
|---|---|---|---|---|---|
| | Market Penetration (%) | | | | |
| Headway (s) | 100% | 80% | 60% | 40% | 20% |
| 1.25 | 65.310 | 65.220 | 65.190 | 65.110 | 65.090 |
| 1 | 65.946 | 65.707 | 65.469 | 65.234 | 65.047 |
| 0.75 | 68.153 | 66.901 | 66.255 | 65.621 | 65.123 |
| 0.5 | 72.277 | 70.309 | 68.446 | 66.678 | 65.329 |

*Table 11: Travel Delay Results at 130% PHV*

| **130% Peak Hour Volume - Travel Delay in seconds** | | | | | |
|---|---|---|---|---|---|
| | Market Penetration (%) | | | | |
| Headway (s) | 100% | 80% | 60% | 40% | 20% |
| 1.25 | 33.776 | 38.457 | 49.286 | 54.041 | 67.551 |
| 1 | 16.807 | 21.174 | 23.530 | 28.691 | 33.614 |
| 0.75 | 13.027 | 13.411 | 17.856 | 23.450 | 25.508 |
| 0.5 | 10.249 | 11.987 | 14.102 | 15.952 | 18.936 |

*Table 12: Average Speed Results at 130% PHV*

| **130% Peak Hour Volume - Average Speed in MPH** | | | | | |
|---|---|---|---|---|---|
| | Market Penetration (%) | | | | |
| Headway (s) | 100% | 80% | 60% | 40% | 20% |
| 1.25 | 65.870 | 65.400 | 65.280 | 65.170 | 65.120 |
| 1 | 66.457 | 66.087 | 65.720 | 65.358 | 65.071 |
| 0.75 | 67.857 | 67.684 | 66.765 | 65.871 | 65.172 |
| 0.5 | 77.763 | 74.124 | 70.811 | 67.781 | 65.538 |

## d. Conclusions

The model used to simulate traffic flows on I-85 shows the benefit of DATP on the corridor. As the traffic volumes were increased, the positive effect of CACC technology also increased on the roadway. The roadways with the highest AADT will see the greatest benefit from the advent of CACC technology.

The modeling showed no delays resulting from DATP operations. At smaller gaps and higher levels of market penetration, average speed and delay for the entire traffic stream showed a benefit. Specifically, no matter the traffic volume on the roadway, implementing CACC technology at a 20% market penetration did not lead to significant roadway efficiency improvements. The only case with beneficial savings at a 20% market penetration is at very low headways. The level where significant improvement occurs in traffic flow at any headway lower than 1.25 seconds is 60% and greater.

The advent of CACC technology on roadways will allow freeways to operate more efficiently. Extremely expensive widening projects normally necessary when congestion inhibits flow on freeways can be avoided. This leaves the potential for these funds to be incorporated into other areas of roadways networks where upgrades would have a greater positive effect.

## e. Plans for Phase II

Looking forward to Phase II of this project, there are many issues to investigate for additional information. These include modeling different times of day, platoons of more than two vehicles, other highway types, and truck lane restrictions.

- In Phase I the modeled truck percentage is the truck percentage seen in the peak hour of overall traffic. Through data obtained from ALDOT, varying truck percentage will be investigated.

Possible choices will include the peak hour of truck traffic of the day, and average hour of truck traffic of the day.

- The modeling focus so far has been two-truck platoons as they have the smallest effect on traffic flow. In Phase II, three-truck platoons will also be modeled.
- All of the model implementation has been focused on freeways as they are the most controlled type of roadway possible. An investigation on a rural arterial that is a major trucking route that is less controlled and includes traffic signals will be done.
- In the initial modeling, the trucks have complete access to the roadway. Restricting the trucks on the roadway to certain lanes of the roadway will also be beneficial to understanding how to best add CACC technology onto the roadway.
- It is important to see how traffic will operate in entry/exit situations. Neither CORSIM nor VISSIM can model the break-up and reforming of platoons "on-the-fly" without additional programming – this will be investigated. If that is not possible, the team should still be able to develop models that specifically focus on the ramp junctions and run platoons by them while traffic tries to enter and exit, but the platoons would be "pre-formed" without the ability for vehicles to "break in".

Finally, findings from other aspects of the overall study that may affect the selection of model parameters will also be addressed.

## *X. Summary*

Phase I of this research found:

- "Truckload" and line-haul "less-than-truckload" fleet operations appear to be a likely fit for early adoption of DATP.
- A trucking industry survey conducted by the team included these findings (which should be considered preliminary since respondents had no experience with DATP at this early stage):
    - 54% of carriers and drivers had an average trip length of less than 500 miles, and 46% were over 500 miles in average trip lengths. Longer trip lengths in DATP operations are more likely to generate greater return on investment.
    - 54% of fleet managers indicated that based on what they knew of DATP, the systems would have a "very positive," "somewhat positive," or no impact on driver retention. 39% of fleet manager respondents feel that drivers are very likely, likely, or moderately likely to use a DATP system. Owner-operator responses for driver retention or usage were on the opposite end of this scale, however.
    - Owner-operators expected a mean DATP payback period of 10 months, while fleet respondents had a mean expectation of 18 months.
- Typical automotive radar shows good tracking ability at headways expected in DATP operations.
- In aerodynamics simulations, the follower vehicle appears to see large amounts of drag reduction, even at larger distances. At closer distances these savings are beneficially compounded by lead vehicle drag reduction. The inter-vehicle distances required for leader fuel savings do not appear to be below the margin of safety for the DATP system to be operated.
- Using data of actual truck movements on a section of highway, platoon formation modeling results were promising. Results showed platoon formation of 30-45% in one dataset, with those trucks remaining platooned between 55-75% of the 300-mile road segment.
- Traffic modeling results showed that DATP caused no delays compared to existing conditions. Gaining significant benefits in traffic flow start to appear at truck market penetrations of over 60% with headways lower than 1.25 seconds (approximately 100 feet at 60 mph); DATP headways are expected to be much lower than this.

During 2015, Phase II work will focus on:

a. System testing: Phase II focuses on equipping the Peterbilt tractors with the DATP system plus data acquisition, followed by testing performance at the test track in the areas of wireless communications, vehicle control, positioning, driver comfort and safety. Additionally, the team will acquire trailers for testing. On-road testing for fuel economy evaluations will be planned, arranged, and conducted. Driver logs from test runs will be analyzed along with system data to identify any anomalies in system performance or driver acceptance.
b. Human factors: The OSE team will provide driver training, assess driver reactions to operating the system at several points during testing (both on-track and on-road). Interviews will be conducted post-training and after 1-year to understand the impact from both training and hands-on experience towards acceptance, concerns, and potential pros.
c. Wireless communications: In evaluating DSRC performance, on-track testing will seek to stress the system and evaluate for packet loss, message delay, channel congestion, and other performance indices. Algorithms and protocols will be designed that improve scalability of DSRC. The team will evaluate an adaptive strategy that allows the DSRC subsystem to prioritize important safety-related messages differently during distinct driving modes.
d. Aerodynamics modeling: The team will develop models with greater detail to support more in-depth evaluations. This will include platoons of more than two vehicles. These models will be integrated with vehicle models to provide a comprehensive evaluation tool for DATP expected to be useful to system developers.
e. Platoon formation: Future modeling with regard to assessing platoon formation will include extending the analysis of the ATRI-provided truck data for additional highway corridors, such as urban corridors, as well as incorporating differences in fuel economy benefits depending on platoon position.
f. Traffic impacts evaluation: The traffic impacts modeling will address several additional issues in Phase II. These include modeling different times of day, platoons of more than two vehicles, other highway types, and truck lane restrictions. Varying truck percentages and modeling three- truck platoons will be done. While the model implementation so far has been focused on freeways, an investigation on a rural arterial that is a major trucking route that is less controlled and includes traffic signals will be done. Finally, it is important to see how traffic overall will operate in entry/exit situations.

Driver Assistive Truck Platooning, if shown to be commercially viable, could lead to new levels of freight/fleet efficiency and improved mobility for all highway travelers, while substantially reducing trucking-based emissions and enhancing the V2X communications environment. Overall project results will constitute an important step towards realizing this potential.

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# *XII. Appendices*

## A. DATP Concept of Operations and System Requirements

## Executive Summary

### Introduction

This document provides a concept of operations and high-level system requirements for Driver Assistive Truck Platooning (DATP), a form of Cooperative Adaptive Cruise Control (CACC) for heavy trucks. The document has been prepared for the FHWA Exploratory Advanced Research project "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment." The project is led by Auburn University and additional partners are Peloton Technology, Peterbilt Trucks, Meritor Wabco, and the American Transportation Research Institute.

The project is a deployment-focused investigation serving to bridge between previous full platooning research and key factors needed for the trucking industry to begin DATP operations and gain the associated benefits, if proven.

The key research objective for this project is to define a commercially viable DATP system, in both operational and technical terms. Such a system must have effective operational strategies for real world conditions such as finding and coordinating with linking partners, making and maintaining the link, and delinking when requested or necessary. The driver-vehicle combination must at all times react safely to events, even in worst-case scenarios.

As the U.S. gears up for some form of Dedicated Short Range Communications (DSRC) deployment, the advent of DATP on commercial trucks will be a significant factor in early deployment of DSRC for safety and other applications. As discussed in the body of the report, the degree to which first generation deployment of DATP occurs on a within-fleet basis, systems can be deployed prior to any government DSRC-focused regulations. Therefore, by harnessing key aspects of cooperative systems, this work will make a strong contribution to Connected Vehicle deployment in the U.S.

Phase One of the project focuses on defining an operationally and technically feasible system for industry. Phase Two will build on Phase One results to implement a prototype system that meets the user needs and can have maximum positive impact on freight efficiency and mobility. Phase Three will focus on transitioning research results to industry, to include a system validation plan that will guide test and evaluation. This project uses simulation, track testing, and finally highway testing to iterate on strategies for system definition.

The document is organized into two major sections: a) Concept of Operations and b) System Requirements. An Appendix maps research objectives across the project phases plus a potential Commercialization Phase.

## Concept of Operations

The ConOps is a description and rationale of the expected operations of the DATP system. It is intended to support stakeholder discussions aimed at defining a system that is operationally feasible and safe for the road user community including the traveling public.

DATP builds on Adaptive Cruise Control, which has been in use by the trucking industry for about a decade. In DATP, two or more trucks are exchanging data, with one or more trucks closely following the leader. The technology basis includes radar (for longitudinal sensing), V2V communications (for low latency exchange of vehicle performance parameters between vehicles), positioning (sufficient to discriminate in-lane communications from out-of-lane communications), actuation (for vehicle longitudinal control), and human-machine interfaces (with distinct modes for leading or following).

DATP may be attractive from a safety and cost of operations standpoint. In terms of safety, the radar-based system provides an additional level of situational awareness to the driver whether DATP is activated or not. Further, testing in past FHWA EAR research and by project partner Peloton has shown that, due to aerodynamic drafting effects, DATP has the potential to significantly reduce fuel use for both the trailing and leading trucks – road experiments have shown 10% and 4% improvements respectively. Initial analyses indicate that this could translate to fleet savings on the order of $8,000 in fuel/year/truck. Therefore, this type of operation could significantly reduce cost of operations and fossil fuel consumption. DATP can be viewed as “low hanging fruit” for connected vehicles, building on USDOT investments in connected vehicle V2V technology.

However, technology is only useful if it meets user needs. A DATP trucking operation, while relatively straightforward technically, constitutes a major step for fleet operators and drivers: depending on data from another vehicle for the safety of “my” vehicle. A wide range of questions arise: how can my driver find another equipped vehicle? How do I know the other vehicle is DATP-ready? How robust is the system? Can the system adapt to changes in operations? How will the following driver retain situational awareness? How does the job of the lead driver change? How does the system react to passenger car cut-ins and other anomalies?

This ConOps preliminarily addresses these questions, setting the stage for extensive stakeholder involvement in assessing the potential of DATP for long haul trucking operations. Specific technical sections address sensing and computing hardware; driver interface; sensor and actuator software and interfacing; control software; diagnostics and reaction; truck systems, and operational environment. Operations-oriented sections provide four operational scenarios plus user-oriented operational descriptions for drivers and fleet managers.

Selected ConOps topics are summarized below.

> Driver Interface: The driver interface must be intuitive and clean. It is critical that the interface does not distract the driver, and that critical functions can be performed with minimal effort and thought.
>
> System Environment: For the support environment, a key aspect is hardware and software standards for inter-vehicle communication. While standards are not absolutely necessary for deployment of DATP within a single fleet, overall costs could be reduced via standardization. For vehicle to vehicle communications inter-operability, the IEEE 802.11p protocol plus associated standards (IEEE 1609) is vital to ensuring that consistent hardware and protocols are

in use by all users. The SAE J2735 message set defined for V2V safety and other applications may need to be revised as DATP and similar systems evolve and come into use. To make a DATP system interoperable across vendors, additional standardization will likely be needed beyond the existing standards, for specific information needed for the close formation platooning.

DATP Linking: The linking process for DATP will be evaluated extensively within the project. Five scenarios have been defined to guide the effort:

- Trucks leave Terminal together (hub-to-hub)
- Ad Hoc Linking: Trucks find each other on the road
- Ad Hoc Linking via Truck Stop Kiosks
- Shipper-Facilitated Linking for OTR Truckload Operations
- Linking on the MAP-21 Truck Network (corridor-focused approach)

### High Level System Requirements

Drawing upon the Concept of Operations plus the technical approach planned for Phase II of the project, high-level DATP system requirements are provided. These are organized in the following major sections:

a. Driver Role
    a. General Driver Responsibilities
    b. Lead Driver Responsibilities
    c. Rear Driver Responsibilities
b. On-board System
    a. General
    b. Sensing
    c. Positioning
    d. Situation Awareness
    e. Maneuvering and Control
    f. Detection and Reaction to Faults
    g. Human-Machine Interface
c. Inter-vehicle Communications

In some cases, parameters are quantified and in other cases left open subject to the findings of Phase II.

### Project Focus

Going forward, the project analyses and stakeholder outreach will expand upon the topics above with extensive interplay between the stakeholder input process, the analytical research focus, and on-track and on-road testing.

# I. Introduction

This document provides a concept of operations (ConOps) and high-level system requirements for Driver Assistive Truck Platooning (DATP), a form of Cooperative Adaptive Cruise Control (CACC) for heavy trucks. The document has been prepared for the FHWA Exploratory Advanced Research project “Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment.” The project is led by Auburn University and additional partners are Peloton Technology, Peterbilt Trucks, Meritor Wabco, and the American Transportation Research Institute.

The project is a deployment-focused investigation serving to bridge between previous full platooning research and key factors needed for the trucking industry to begin DATP operations and gain the associated benefits, if proven.

As the U.S. gears up for some form of Dedicated Short Range Communications (DSRC) deployment, the advent of DATP on commercial trucks will be a significant factor in early deployment of DSRC for safety and other applications. As discussed in the body of the report, the degree to which first generation deployment of DATP occurs on a within-fleet basis, systems can be deployed prior to any government DSRC-focused regulations. Therefore, by harnessing key aspects of cooperative systems, this work will make a strong contribution to Connected Vehicle deployment in the U.S.

Phase One of the project focuses on defining an operationally and technically feasible system for industry. Phase Two will build on Phase One results to implement a prototype system that meets the user needs and can have maximum positive impact on freight efficiency and mobility. Phase Three will focus on transitioning research results to industry, to include a system validation plan that will guide test and evaluation. This project uses simulation, track testing, and finally highway testing to iterate on strategies for system definition.

The key research objective is to define a commercially viable DATP system, in both operational and technical terms. Such a system must have effective operational strategies for real world conditions such as finding and coordinating with linking partners, making and maintaining the link, and delinking (by driver choice and when a system fault/limitation occurs). The driver-vehicle combination must at all times react safely to events, even in worst-case scenarios.

The document is organized into two major sections: a) Concept of Operations and b) System Requirements.

# II. DATP Concept of Operations

## II.A. Concept Overview

This ConOps is a description and rationale of the expected operations of the DATP system. It is intended to support stakeholder discussions aimed at defining a system that is operationally feasible and safe for the traveling public.

DATP builds on Adaptive Cruise Control, which has been available to the trucking industry for several years (approximately 100,000 ACC-equipped Class 8 trucks are on the road now). DATP uses 5.9 GHz DSRC (IEEE 802.11p) vehicle-to-vehicle wireless communications combined with automotive radar systems to allow two trucks to safely follow each other at shorter headways than unassisted drivers can manage, while the driver retains steering control. Wide-area communications allow vehicles to identify and coordinate linking opportunities with other vehicles, both within a fleet or ad-hoc.

More specifically, the technology basis includes radar (for longitudinal sensing), 5.9 GHz DSRC (IEEE 802.11p) V2V communications (for low latency exchange of vehicle performance parameters between vehicles), satellite positioning (sufficient to discriminate in-lane communications from out-of-lane communications), actuation (for vehicle longitudinal control), and human-machine interfaces (with distinct modes for leading or following). V2V communications ensures that at the moment braking is initiated in the lead truck (prior to braking actually occurring due to delays in typical braking systems), braking is initiated in the rear truck virtually simultaneously; the two trucks decelerate together. The same is true for acceleration.

Since the 1990's, truck platooning has been the objective of research and evaluation globally. Work to date has focused on several fully automated trucks running at very close headways with data flowing from the lead truck to all following trucks. While this has been shown to be feasible at a technical level, the premise of DATP is that taking this technology to full commercialization requires a simpler technical approach which bridges from trucking operations currently in use today (ACC) to the DATP operational mode with only two trucks linked together.

DATP may be attractive from a safety and cost of operations standpoint. In terms of safety, the radar-based system provides an additional level of situational awareness to the driver whether DATP is activated or not. Further, testing in past FHWA EAR research and by project partner Peloton has shown that, due to aerodynamic drafting effects, DATP has the potential to significantly reduce fuel use for both the trailing and leading trucks – road experiments have shown 10% and 4% improvements respectively. Initial analyses indicate that this could translate to fleet savings on the order of $8,000 in fuel/year/truck. Therefore, this type of operation could significantly reduce cost of operations and fossil fuel consumption. DATP can be viewed as "low hanging fruit" for connected vehicles, building on USDOT investments in connected vehicle V2V technology.

To address one particular safety aspect commonly raised with regard to platooning operations: cut-ins by passenger vehicles are unfortunately a too common scenario in highway operations. DATP builds on radar-based Adaptive Cruise Control (ACC) and collision mitigation systems (CMS) which aggressively brake in an impending crash situation. Thus, ACC/CMS systems assist the truck driver in braking as quickly and forcefully as possible to a cut-in vehicle. Due to the laws of physics, not all collisions can be avoided but these systems can at least reduce the energy in a crash which is unavoidable. It should be noted that the potential for a near-crash or crash due to passenger vehicle cut-ins does not change with DATP compared to existing ACC/CMS systems; however the potential of cut-ins may be somewhat reduced due to the closer spacing between trucks. At some point in the future when all cars have V2V, response to the cut-in can potentially occur even earlier. Therefore, for purposes of this research, a "safe" system, whether ACC, CMS, or DATP, is one which responds to a developing crash situation as quickly as possible (and significantly faster than a human driver could) to either avoid the crash or slow the vehicle speed to reduce the energy in a crash.

In essence, DATP combines developments in collision avoidance technology, advanced control algorithms, and real-time communications to enable the trucking industry to take an incremental step towards vehicle automation in a manner that is economically attractive. However, technology is only useful if it meets user needs. A CACC trucking operation, while relatively straightforward technically, constitutes a major step for fleet operators and drivers: depending on data from another vehicle for the safety of "my" vehicle. A wide range of questions arise: how can my driver find another equipped vehicle? How do I know the other vehicle is DATP-enabled? How robust is the system? How can the system adapt to changes in load? How will the following driver retain situational awareness? How does the job of the lead driver change?

This DATP ConOps preliminarily addresses these questions, setting the stage for extensive stakeholder involvement in assessing the potential of DATP for long haul trucking operations.

## II.B. Operational Needs

This section defines and describes the major operational components of the trucking industry, including stratifications for sector, fleet size and vehicle configurations, and how these relate to potential DATP operations.

In 2012, the $642.1 billion U.S. trucking industry accounted for nearly 81 percent of the nation's freight bill and delivered 69 percent of all domestic freight tonnage.[3] This freight was hauled by nearly 24 million commercial trucks[4] and over 3 million drivers.[5] Nearly 7 million people were employed in jobs that were trucking-related.[6]

Looking forward, overall freight volume forecasts indicate 20 percent growth by 2024; the trucking industry's share of freight tonnage is expected to increase even more. With infrastructure capacity improvements projected at less than 5 percent during this same time, the nation's transportation system will be hard-pressed to meet the needs of an expanding economy. Thus, advances in technology could help improve or maintain efficiency in freight movement.

Intelligent transportation technologies relating to wireless communication, advanced sensors and driver feedback are already used in the trucking industry, but when fully integrated could have the potential to- among other benefits- increase reliable, on-time delivery of goods; improve driver safety; and aid in compliance with federal regulations. Upon successful integration of these disparate systems, a sophisticated truck management system can be realized. However, incorporating these technology solutions across a large and diverse industry presents several challenges. For example, the distinct differences in operational needs among hundreds of thousands of carriers must be considered when developing an integrated truck management system technology. These operational distinctions can generally be discussed in three categories: sector; fleet size and vehicle configurations. The following sections describe the nuances of these operational characteristics and their relationship to proposed DATP operations.

### II.B.1. Sectors

Motor carriers are often segmented into the following over-lapping groups: for-hire carriers, private fleets, owner operators, courier fleets, and other specialized sectors of carriers. The two largest segments of the industry are for-hire carriers (34%) and private fleets (53%).[7] For-hire carriers move freight under contract for the general public; essentially transporting shipments for others for a fee. Private fleets transport goods for their own company. Unlike for-hire fleets, private fleets support goods movement for industries where primary business activities are not transportation. For example, national and regional grocers such as Wal-Mart, Kroger, and Publix all utilize their own private fleets to move their goods. Trip lengths are less than 500 miles for the majority (75%) of private hauls.[8]

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[3] *American Trucking Trends 2013*. American Trucking Associations. Arlington, VA. (2013). Pg V.
[4] Ibid. Pg V.
[5] Ibid. Pg VI.
[6] Ibid. Pg VI.
[7] Ibid. Pg 3. Figure 1-2, Distribution of U.S. Motor Carriers by Sector.
[8] *Trucking 101 – An Industry Primer*. Transportation Research Board of the National Academies. Transportation Research Circular E-C146. Washington, D.C. (2010). Pg 18.

For-hire carriers can be further stratified by sector, vehicle configurations and/or commodity types. Two of the largest sectors of the industry are described as truckload and less-than-truckload (LTL) carriers. Truckload carriers can have numerous customers; however, they typically dedicate a truck and trip to a single customer at a time. These shipments are often large enough to meet truck capacity leaving little or no room for other shipments. LTL carriers group smaller shipments (generally shipments average 1,000 pounds[9]) of multiple customers together on the same truck and move those shipments through a hub and spoke operation.

Finally, many other carriers (13%)[10] transport specialized shipments, such as refrigerated goods, agricultural goods, hazardous materials or goods/equipment that require flatbed trailers.

### II.B.2. Fleet Size

Nearly 24 million commercial trucks were registered and used for business purposes in the U.S. in 2011.[11] Of these, 2.3 million were Class 8 "heavy" trucks that typically operate in a tractor-semitrailer configuration.[12] Over 1.5 million heavy-duty and tractor-trailer truck drivers were employed in 2013.[13] The industry also registered 5.78 million commercial trailers in2010.[14] Commercial trucks (all classes) logged nearly 398 billion miles in 2010.[15] Of these miles, Class 8 trucks drove more than 99 billion miles.[16]

Since deregulation, the number of motor carriers has grown exponentially over the past three decades. The number of carriers has grown from fewer than 20,000 interstate carriers (prior to the Motor Carrier Act of 1980) to over 442,000 for-hire interstate carriers and 700,000 private fleets registered with the USDOT as of January 2013 (as well as 165,000 "other" motor carriers).[17] The industry is comprised mainly of small, locally owned fleets with the vast majority (91%) operating six or fewer trucks. [18] Overall, the number of carriers grows by about five percent annually while the number of trucks-in-service increase by about three percent.[19] The majority of the trucks-in-service growth has been experienced in the regional and long-haul segments.[20]

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9 Ibid. Pg 21.
10 *American Trucking Trends 2013*. American Trucking Associations. Arlington, VA. (2013). Pg 3. Figure 1-2, Distribution of U.S. Motor Carriers by Sector.
11 Ibid. Pg V.
12 Ibid. Pg V.
13 U.S. Department Of Labor, Bureau of Labor Statistics, Occupational Employment Statistics. (SOC code 533032) Available online: http://data.bls.gov/oes/
14 Ibid. Pg 24.
15 Ibid. Pg V.
16 Ibid. Pg V.
17 Ibid. Pg VI.
18 Ibid. Pg VI.
19 .*Safety for the Long Haul; Large Truck Crash Risk, Causation, and Prevention*. Knipling, R. American Trucking Associations. Arlington, VA. (2009). Pg 6.
20 Ibid. Pg 6.

### II.B.3. Vehicle Configurations

A variety of truck configurations are operated in the marketplace. Straight trucks are a single unit truck comprised of an integrated power unit and trailer. Combination trucks utilize discrete tractors and trailers that can take many forms. For trucks and their cargo weighing up to 80,000 lbs, travel by a standard five-axle (18-wheel) configuration is allowed on the National Highway System (with several exceptions) across all 50 states. Over-size trucks like longer combination vehicles (LCV) are only permitted to operate in certain states, on certain routes and may require special permits. Some specialized carriers are dedicated to hauling hazardous materials and require special equipment and permitting as well.

Recent data indicate growth in the truck population across all vehicle configurations. Overall, registrations for class 3-8 trucks were up 2.8 percent from those of the same period in 2012 with growth strongest among the Class 4 vehicles.[21] Class 8 vehicles were the only class to lag from 2012 levels of new registrations[22]; however the total number of Class 8 trucks in operation grew to a four-year high (3.63 million)[23] by the end of 2013's third quarter.

## II.C. User-Oriented Operational Description

This section describes potential DATP operations, from the viewpoint of the truck driver as well as fleet personnel. This analysis is based on trucking industry stakeholder input.

Finding technology solutions for the large and diverse trucking industry can be present myriad considerations that are unique to each individual carrier and their operations. There are however several overarching themes which will be important to any carrier or driver deploying the DATP system.

Based on stakeholder input it is clear that improving safety will always be a primary objective for the trucking industry. However, in an industry consisting mostly of smaller carriers with tight operating margins, the cost of new technology systems is also an important consideration. Given the attitudes expressed in stakeholder discussions, DATP systems are most likely to be adopted first by larger carriers who tend to have capital available for technology purchases. Further exploration of motor carrier operations is likely to reinforce the perception that smaller carriers and owner-operators who operate fewer trucks with less capital, or private fleet hauls and LTL shipments in urban areas, may not fully reap the benefits of DATP systems.

DATP may be best deployed in larger regional/long haul carriers with more trucks in their fleets, possibly along the same routes, reducing the need to couple with competitors' vehicles or delay trips in order to participate in a platoon.

Some carriers offer a driver incentive for improved fuel economy; offering an incentive to drivers for using the DATP system has received support in stakeholder discussions.

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[21] "Commercial Vehicle Registrations Increase Nearly 3%, Best Since 2007". TruckingInfo. November 25, 2013. Available Online: http://www.truckinginfo.com/channel/fleet-management/news/story/2013/11/commercial-vehicle-registrations-increase-nearly-3-best-since-2007.aspx

[22] Ibid.

[23] "Class 8 Fleet Grows to 4-Year High". Transport Topics. November 25, 2013. Available Online: http://www.ttnews.com/articles/basetemplate.aspx?storyid=33570

### II.C.1. Drivers

#### Finding a link partner

The system must find link partners in a way that is minimally disruptive to the operations of the fleet. Initial scenarios considered to facilitate linking are within a fleet at their facility, at truck stops and rest stops or other places where the trucks are stationary, or over the open road.

Within a terminal, DATP can be a formal part of the dispatch & logistics system for fleet operations, or it can be more ad-hoc. Timing of departure may be adjusted to coordinate the trucks, or scheduled groupings of trucks can be designed and implemented.

At trucks stops, rest stops, inspection stations, or anywhere else trucks are stationary, they could be coordinated, using a third-party system, to find linking partners.

Over the road, the driver can be notified of the opportunity to link with a truck ahead or behind. If they both indicate they want to link, then they can move to the next phase of operation. The distance where this makes sense for a fleet is to be determined.

#### Arranging to be in linking position

Industry input indicates some concern from fleets about the arrangement of trucks (who's in front, how close are they, etc.). The configuration of platoons must be done in a way that is comfortable to the drivers to address their concerns about vehicle control.

Because the trucks are partially automated (longitudinal), once they have elected to link with a partner they must arrange to be in proximity with that truck. For example, if they are a few miles apart on the highway, the front truck can decrease its speed to rendezvous with the trailing truck. The key tactic is for them to get within DSRC range, and to be in the correct order (of trailing and leading truck). The system must help or instruct the driver of the needed arrangement.

There may be a time window after coordination in which the trucks must link. If for example the trailing truck is delayed, the front truck can be notified so that it has the option to link with another truck or to proceed un-linked.

#### Link Engagement

Once in position, the drivers (of both trucks) must select to engage the link between the trucks. The design of this engagement selection and the resulting action is very important to increase the confidence of the driver, again to address concerns reflected heard in stakeholder discussions about vehicle safety and control.

When a linking request is received, relevant information regarding the potential linking partner shall be displayed on the DATP User Interface for the lead driver. The lead driver can accept or not accept the request, based on traffic conditions or other factors.

#### Linked Driving

While linked, the driver experience must be acceptable in both the lead and/or follow positions.

While linked, the rear driver's task is very similar to that with adaptive cruise control. The driver is steering, but the braking and acceleration are fully automated. The system may communicate to the driver about the actions of the system, in order to increase confidence in the system.

Most critical to this is a video feed from the other truck. By relaying the front truck's view to the rear driver, the driver can see what is coming ahead on the road or in the shoulder.

Initial trials of this type of system indicate that the driver uses this view in much the same way the mirrors are used. The driver can scan from front scene to each mirror and to the video display. Initial testing suggests that the placement of this screen is important to ensuring it works well in the driver's scanning.

The front driver's task is unchanged from typical driving. It may be desirable to require cruise control activation on the front truck to ensure a smooth acceleration/deceleration profile to improve the performance of the platooning.

If the front vehicle changes lanes, the rear driver will usually also desire to do so. The technology used allows the trucks to continue to sense and communicate with one another in most cases where the front truck has changed lanes. Whether it is desirable to maintain the linked mode, or better to break the link and allow an easy way to re-engage the link, needs to be determined through prototyping and trials.

The drivers' responsibilities while linked are:

a. General
    a. The driver must remain vigilant to the road situation at all times.
    b. Drivers must monitor and respond to DATP system messages.
b. Lead Driver
    a. The lead driver shall perform lane changes gradually when conditions allow, as needed.
    b. The lead driver has the option to drive fully manually, or to engage collision warning and/or adaptive cruise control systems.
    c. The lead driver is responsible for all aspects of driving their vehicle: steering, throttle, and brakes.
c. Rear Driver
    a. Inter-vehicle spacing of vehicles within the platoon shall be acceptable to the driver.
    b. The rear driver is responsible for lateral control of the vehicle at all times. Braking and acceleration shall be fully automated when DATP assistance is engaged.
    c. The rear driver shall monitor the road ahead via a video feed from the lead truck as needed to maintain situational awareness .
    d. The rear driver has the ability to control throttle, braking, and steering at any time; steering is driver's responsibility at all times.

### Delinking when needed/desired

All delinking operations must be smooth and predictable to the driver, providing sufficient time to retake control of the vehicle.

The driver of the rear truck should have the ability to intuitively and comfortably de-link when desired. The trucks may be delinked for one of several reasons:

- Pedal input: If the driver of the rear truck presses the brake pedal, the trucks will smoothly delink. The trajectory for this will depend on how hard the front truck is braking. The reaction to other pedals pressed during this delinking, and other scenarios, will be determined during the project and reflected in the requirements document.
- Driver Interface input: The driver can press a button (or virtual button on a touchscreen) to choose to delink the trucks. If the front truck driver chooses to delink, the reaction of the rear truck may be immediate, or the system could require a confirmation from the rear truck before delinking.
- System fault: If there is a detected problem with either the system or with the truck itself, the trucks can smoothly delink and the driver is appropriately informed
- Conditions change: If the system detects that the traffic is too dense, the weather is adverse, or other conditions, it can delink the trucks, and the driver is appropriately informed.

The system shall clearly indicate driver responsibilities to the driver in the event of system-induced changes to operational mode.

For a system fault or change of conditions, it may be desirable to have a more aggressive delinking option to ensure safety. This may involve more rapid deceleration to separate the trucks more quickly, and/or a shorter time period in which the driver must retake control.

In any event of delinking, the driver is not expected to react quickly, but is expected to be available to retake longitudinal control at some point (this time window will be determined during the project). Until the driver reacts, the truck is increasing separation to a safe manual following distance, either by coasting or active braking.

For lane changes in which the system delinks the platoon, drivers shall be informed and then be offered the option for easy re-engagement once the lane change is complete.

In an emergency lane change, the system shall automatically decelerate the rear vehicle and disconnect the platoon. The rear driver then has the responsibility to change lanes if necessary, with the additional time afforded by the deceleration.

### Responding to Passenger Car Cut-Ins

When a vehicle (presumably a passenger car or motorcycle but potentially a truck) cuts between the platooning trucks, the rear truck will detect this situation and automatically increase following distance to a safe gap. No action on the part of the driver is needed.

When the cut-in vehicle is no longer between the trucks the driver can “resume” platooning operation either automatically or manually through the driver interface. In these situations it is possible that the trucks will get out of DSRC range. If this occurs, then it will need to manually re-enter DSRC range before relinking.

### Relinking

When the vehicle has been already linked, the relinking operation should be simpler than the initial linking. For example this may not require the driver to re-select with which truck to link, but only selecting to re-engage the link.

### II.C.2. Fleet Manager

#### Managing Equipped Vehicles

Survey results show that fleet managers want significant fuel savings. To obtain these benefits, a fleet manager will want to maximize the period of time in which trucks are linked. S/he can do so via several choices made on a daily, weekly or monthly basis.

##### *Which Trucks to Equip*

Factors include miles traveled per day and per year, age of the equipment or time until they retire or sell the equipment the driver of that truck, and the cargo commonly hauled by that truck.

##### *Where to Deploy Equipped Trucks*

The fleet manager may maximize the benefit by deploying the trucks in areas with appropriate roads (wide open interstates, relatively little road grade, low traffic). Also in consideration are areas where the trucks drive the most miles (or most miles at highway speeds). A key target will be utilizing trucks that have regular-route scheduling.

##### *How/When to Dispatch Equipped Trucks*

The choice of when to dispatch a truck is highly integrated into a fleet's proprietary operations, and closely associated with shipper delivery requirements. But insofar as they have freedom to adjust it, they can maximize use of the system in a few ways:

- Dispatch trucks together, so they can link easily, potentially for their whole route
- Send trucks at times of low traffic

#### Finding a Linking Partner

The fleet manager will usually only be involved in arranging linking partners by adjusting dispatch timing, or routing.

## II.D. System Overview

This section outlines an initial high level technical approach to focus the efforts in the project to meet the objectives described above. This technical approach will be refined as a major component of the project.

At its core, the DATP system interfaces with the truck, with added components, with the driver, and with wide area networks. A high level DATP system diagram (Figure 1) is shown below, followed by a diagram showing major system components (Figure 2).

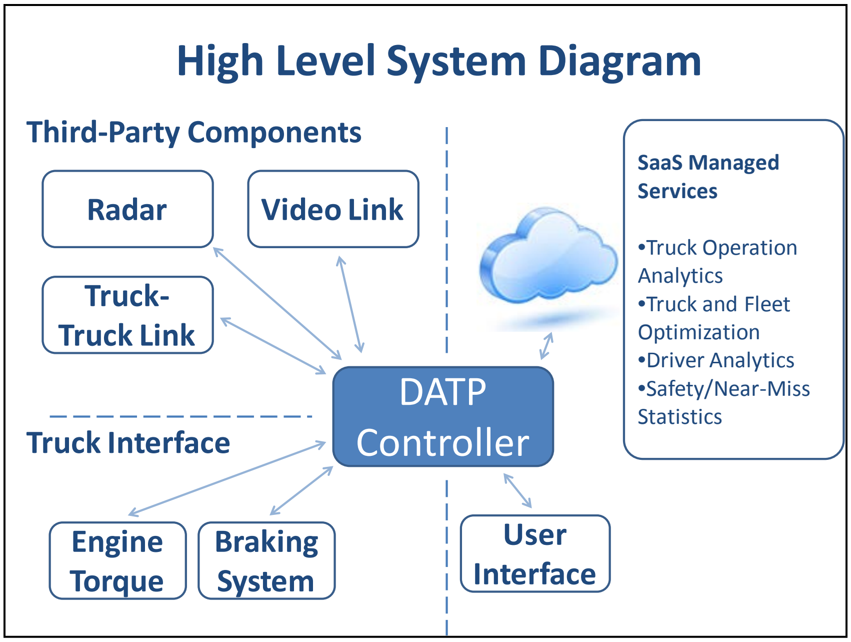


Figure 1: High Level DATP System Diagram

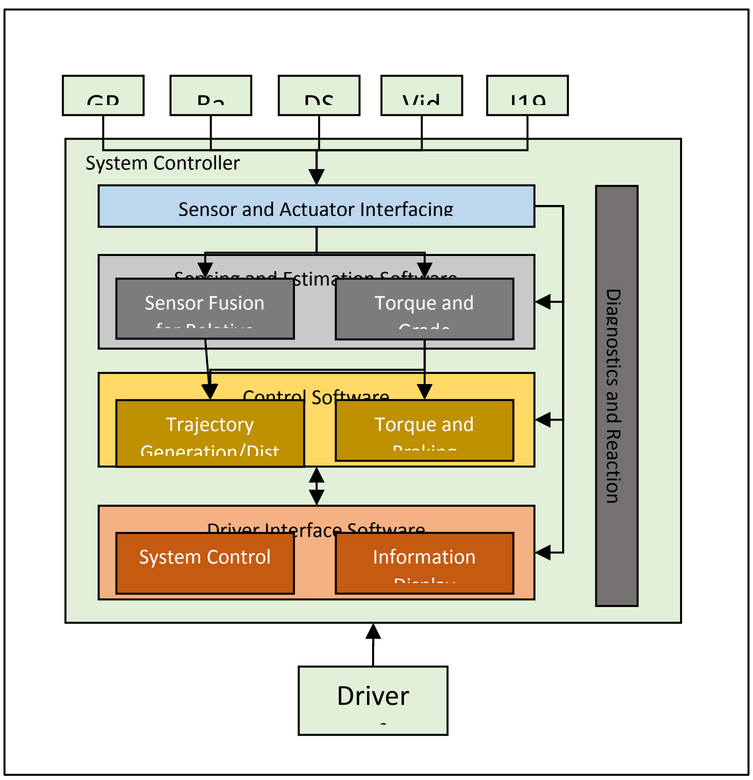


Figure 2: DATP Major System Components

### II.D.1. Sensing and Computing Hardware

#### Position and Speed

An off-the-shelf GPS receiver may provide sufficient accuracy position information for coordination of the two trucks, and quite smooth and accurate velocity information. This requires a receiver and an antenna installed on the exterior of the truck. These receivers typically have a serial interface.

For more accurate positioning, various types of differential GPS may be used, including approaches that use satellite broadcast corrections, fixed base stations, or differential GPS between the two vehicles.

#### Relative Position and Speed

Automotive radar units from various providers can provide distance and relative speed to a large number of targets simultaneously. These have been well developed initially for passenger car Adaptive Cruise Control and also applied to commercial vehicle ACC. They typically have a CAN interface and are installed in the front bumper.

#### V2V Communication

Automotive grade DSRC radios are well suited for this application, with more than sufficient range, and excellent bandwidth and reliability. Typical antenna installations use one antenna on each mirror to preserve line of sight even with a trailer attached. The radios handle the antenna diversity as well as the standard protocol.

#### ECU

Computing needs are relatively low by modern standards, so an automotive type ECU has sufficient processing power for this type of application. In general it needs to have one or more CAN interfaces and a serial interface.

#### Driver Interface

The driver interface must be intuitive and clean. It is critical that the interface and all displays do not distract the driver, and that critical functions can be performed with minimal effort and thought.

Any system-induced changes to operational mode (such as delinking or fault handling) shall be indicated appropriately and be understandable to the driver; the driver's responsibilities in these cases (if any) shall be clearly indicated.

For lane changes in which the trucks stay in platoon during the whole event, drivers will be clearly informed of the status.

If needed, a driver information display plus response buttons will support the linking process (alternatively, all link coordination may be done by the dispatcher or a linking service). When no trucks are within linking range, the display will show suggested trucks to link with (identified over cellular data connections). This will support the coordination process.

Once a truck is in range, but the system is unavailable for linking, the screen indicates the reason for the unavailability. Once conditions are met (system booted up, speed appropriate, etc.), the screen displays a "ready to link" selection to the front driver.  Once s/he has indicated readiness to link, the rear driver is given the option to initiate the link, and it is engaged.

When the link is disengaged, the reason for this will be displayed to the driver for an appropriate period of time.

#### Video Display

The video display can be used to show each driver the view from the other truck's front perspective.  For each driver this serves a different purpose:

- For the rear driver this allows a view "through" the front truck, to see what is immediately above the front truck and also what is coming up on the shoulder, on-ramps, etc.
- For the front driver this shows the view from behind his truck, showing his blind spots on each side of his truck.

### II.D.2.  Sensor and Actuator Interfacing

The hardware and software components to interface with the sensors are fairly straightforward.  Some sensors are CAN based, others serial.  The data bus of the truck itself follows the J1939 protocol, which is based on CAN.

If an automatic or automated manual transmission is used, it may be desirable to command specific gear shifts (for example to have the two trucks shift at the same time), and the command ability for these transmissions can be through J1939 or a proprietary message.  J1939 defines an XBR message for External Brake Request.  Depending on system design it may be desirable to have a more robust interface, or J1939 XBR may be sufficient.

### II.D.3.  Sensing and Estimation Software

#### Sensor Fusion for Relative Positioning

This software combines sensors (GPS, radar) to provide an accurate and smooth determination of relative positioning and speed between the two trucks.

#### Torque and Grade Estimation

Key data to send from the front truck to the rear truck is the engine torque.  Communicating this in the proper way, taking into account road grade, is critical to rapid response by the rear truck.

### II.D.4.  Control Software

#### Trajectory Generation/Distance Selection

Before commanding torque and/or braking, a desired position and speed between the trucks is determined by the trajectory/distance algorithm.  This is needed to ensure smooth motion of the trucks, in a way that is comfortable to the driver.

#### Torque and Braking Application

With the desired trajectory/distance determined, this software commands a mix of engine torque, retarder, gear selection (if an automated transmission), and/or braking to meet the desired trajectory.

During a lane change the system shall maintain the platoon as appropriate to maintain safety of the trucks.

#### II.D.5. Diagnostics and Reaction

The diagnostics fall into three main categories.

##### Truck Faults

The J1939 bus of the truck will contain faults from the stock ECU of the truck. These include items such as emissions issues which can impose limits on torque production or otherwise impact the operation of the platooning system. These can be read directly from the J1939 bus, and conform to the standard. These only include faults that are detected by the ECU, so it is critical to also detect important mechanical faults.

##### System

Diagnostics for the platooning system are critical. These include its ability to communicate with the vehicle bus, sensors, actuators, and more. Specifics are provided in the System Requirements section.

##### Truck Systems

The truck contains a limited set of diagnostics, so it is critical to have additional diagnostics for key systems such as the brakes. These may include

- Brake condition diagnostic
- Engine braking diagnostic
- Engine torque production diagnostic

##### System Response to Faults

The system response to these faults will be designed to be intuitive to the driver. This is critical to ensure that the driver can react safely. Exact responses are to be determined through the course of the project.

### II.E. Operational Environment

A key enabler for this type of system is to restrict operation to safe areas, either through fleet policy and driver training or through the system imposing the restrictions automatically. These restrictions may come from state or federal regulations, or from input from safety experts. Initial criteria considered are noted below; these will be further defined through stakeholder interactions:

##### Road

Initial thoughts are to restrict operation to divided US Highway and interstates, including maintaining the platoon in a freeway-to-freeway type interchange. Additional restrictions are on steep downgrades, due to potential issues with brake overheating (plus there is no fuel savings to be had if the engine is already not burning any fuel). Uphill is less of an issue but can also be restricted. Sharp curves can also be excluded. For all of these restrictions specific dynamics and braking capability of a given truck will be critical to deploying safely.

Over-weight rules for bridges may need to be addressed due to the combined weight of the platooning pair. However, with knowledge of upcoming bridges and mass of each vehicle, potentially the platoon can be opened up just prior to traversing the bridge.

### Weather

Adverse weather conditions that impact traction, such as ice or snow, may be excluded from DATP operations. Very strong winds could be excluded if necessary. Each of these conditions could also trigger a change to the system operating parameters (for example, adjusting the following distance).

### Driver

Driver should have appropriate training / familiarity with the system as defined by the fleet manager. This will be determined through this project in discussions with fleets and drivers.

### Traffic

Dense traffic may be excluded from DATP operations, or the systems can adjust the operating parameters (such as traveling speeds and following distance). Parameters for this requirement will be determined over the course of this project.

### Work Zones & Other Temporary Operating Conditions

Given the higher variability in driving conditions that are presented by work zones, incident areas and other temporary traffic-controlled areas, the DATP system may adjust following distance, speed, or other parameters depending on the specific situation.

### Ordering Based on Braking Ability

DATP represents an opportunity (and a need) to ensure that the better braking truck is in the rear. In this way if a full hard stop is required, there is a higher probability that the trucks safely come to a stop. Estimating this braking ability is a key part of the system concept, and can be based at least in part on gross vehicle weight, type of brakes installed, and conditions.

## II.F. Support Environment

A key aspect of the support environment is hardware and software standards for inter-vehicle communication. While standards are not absolutely necessary for deployment of DATP within a single fleet, overall costs could be reduced via standardization.

For vehicle to vehicle communications inter-operability, the IEEE 802.11p protocol plus associated standards (IEEE 1609) is vital to ensuring that consistent hardware and protocols are in use by all users.

Regarding messaging, a fleet using DATP could define their own message sets. However, standardization of messages to support DATP operation could reduce risk and lower development costs. The SAE J2735 message set defined for V2V safety and other applications my need to be revised as DATP and similar systems evolve and come into use. The exact message set is to be determined for this project will be determined in Phase II; these messages may contribute to extensions to J2735.

Similarly, cyber security could be handled in a customized fashion by a fleet choosing to only link within-fleet for DATP operation. For broader-based operation, security protocols and standards similar to those in development for V2V safety could play a role.

## II.G. Operational Scenarios

The key objective of the DATP system is to pair appropriate trucks in order to maximize benefits. While multiple ad hoc scenarios can be conceptualized, the initial scenarios being proposed for DATP operations are:

## Trucks leave Terminal together (hub-to-hub)

This scenario is commonly available for LTL and parcel carriers, and occasionally for private fleets who have a sufficient density at origin/destination facilities. In the LTL/parcel carrier example, once freight sorting is complete, trucks with similar routing/dispatching activities can be paired at the terminal. Typically LTL trucks depart once they're loaded and paperwork is complete, but through modifications to routing/dispatching activities, they could likely be dispatched in pairs.

These trucks would then manually drive to the highway and proceed to whatever initial portion of the highway is appropriate for linking. Once in a linkable stretch of road, and in the correct order, they would engage the link and continue down the road until either they arrive at their exit, or leave the linkable zone.

Since private fleets represent more than 50 percent of all trucking companies on file with the U.S. DOT, this becomes a critical target population. In the private fleet scenario, private fleets often leave distribution centers (DCs) in groups, and many of these DCs are deliberately located along low-density or rural interstates. As noted in the LTL scenario, private trucks could commence linkages at the DC and proceed in link mode until geo-location data diverges and automatically notifies the drivers and/or de-links the trucks. Because medium to large private fleets typically use dispatching software systems, it would be logical to have a DATP application incorporated into the fleet's management system.

## Ad Hoc Linking: Trucks find each other on the road

Trucks (either from within a fleet or between fleets) can be driving over the road and automatically discover other linkable trucks. When each truck elects to link, the other driver is notified.

Once they have both selected to link, they manually coordinate to be near each other. The driver of the front truck can reduce his speed, or the driver of the rear truck can increase his speed if within allowable limits.

Once the trucks are within DSRC range, the system notifies them of which truck should be in front. They manually get in position.

Once in position, the front driver can select to engage the link. The rear driver then has the option to engage the link, which causes engine torque and braking to come under automatic control. After engaging the link, platooned driving would continue until either they get to their exit, or leave the linkable zone. In both cases, linking would be initiated by the drivers.

## Ad Hoc Linking: Truck Stop Kiosks

Private truck stops could represent an ideal scenario for ad hoc linking. These facilities concentrate trucks that share similar routes and often experience waves of arrivals and departures; such concentrations could facilitate ad hoc linkages among willing participants. While the DATP systems could "see" other DATP-installed trucks, a more efficient approach might be to utilize a kiosk where truck drivers could input their routes and departure times, and the kiosk could generate pairings (and notify the appropriate drivers). From the truck stop, drivers then could proceed to the intended roadway and commence the link at the appropriate time.

## OTR Truckload Operations / Shipper-Facilitated

The truckload sector of the trucking industry is experiencing considerable change, including a major driver shortage, diversion to rail intermodalism, and fierce competition with the TL sector. Alternatively, this TL sector meets almost all requirements as a strategic target market for DATP: long trip lengths, rural and suburban corridors, relatively high technology adoption, and high fuel costs.

The TL scenario assumes that competitive issues have been resolved. At that point, the most likely linking opportunities would generate from one of two previously identified scenarios, or a third Shipper-Facilitated approach:

1) Ad Hoc Over-The-Road (en route) Linking
2) Truck Stop Linking
3) Shipper-Facilitated Linking

In the Shipper-Facilitated Scenario, different OTR TL trucks would be identified at mixed fleet shipper facilities, possible using a kiosk system (see Truck Stop scenario), or directly integrated into the shipper freight management system. In both cases, advance approval from fleet executives may be needed. At that point, the process would mirror the Private Fleet scenario.

## Linking on the MAP-21 Truck Network

The existing Federal transportation bill, MAP-21, requires the identification and designation of a national truck network. It is assumed that a large portion of this network would be conducive to an enhanced DATP system, particularly the non-urban and non-mountainous corridors within the network.

Initial steps in developing such a DATP network would be to identify appropriate corridors within the MAP-21 network, using GIS software and data layers. Then, an overlay of DCs, truck terminals and freight generators (including operator contact information) would be overlaid on the corridor shapefile. At that point, an outreach program targeting like-minded fleets could be commenced, possibly with public sector grants or subsidies.

# III. DATP System Requirements

Drawing upon the Concept of Operations plus the technical approach planned for Phase II of the project, high-level DATP system requirements are provided here. These are organized in the following major sections:

d. Driver Role
    a. General Driver Responsibilities
    b. Lead Driver Responsibilities
    c. Rear Driver Responsibilities
e. On-board System
    a. General
    b. Sensing
    c. Positioning
    d. Situation Awareness
    e. Maneuvering and Control
    f. Detection and Reaction to Faults
    g. Human-Machine Interface
f. Inter-vehicle Communications

Following these sections, a block diagram (Figure 3) is provided to illustrate data flows between major subsystems.

Specific requirements for operation of any off-board system to identify and recommend linking partners are not within the scope of this document.

While requirements for a specific system design would be quite detailed, the purpose of the project is to assess the DATP concept rather than to lead to a specific system design; therefore, the requirements and functions specified in this document are at a fairly high level. Numerical values are indicated where appropriate; in some cases, an "X.XX" is shown instead of a value subject to the findings of system testing to occur in Phase II of this project.

## III.A. Driver Role

### III.A.1. General Driver Responsibilities

III.A.1. The driver shall take over full control at any time he or she is not confident the system is operating properly.

III.A.2. For ad-hoc linking, drivers shall indicate to the DATP system their availability to link. When the system finds a nearby partner, the relative position of the partner is indicated. Drivers (if they accept the link recommendation) shall adjust speed and/or route to come within linking range.

III.A.3. For pre-arranged linking (at depot or via a kiosk), drivers shall maneuver such that the vehicles enter the highway in close proximity.

III.A.4. During the linking process, the system shall indicate which vehicle must be in the lead and drivers must maneuver accordingly.

III.A.5. Once in position to link, the drivers (of both trucks) shall indicate to the system their desire to engage the link between the trucks.

III.A.6. The driver shall indicate to the system a desire to delink if they wish to do so for reasons other than system faults.

III.A.7. In any event of delinking, the driver shall be available to retake longitudinal control within XX seconds (this time window will be determined during the project).

III.A.8. Drivers shall monitor side mirrors in compliance with applicable state and local laws.

### III.A.2. Lead Driver Responsibilities

III.A.9. The lead driver shall use turn signals to indicate an upcoming lane change to the rear driver.

### III.A.3. Rear Driver Responsibilities

III.A.10. The rear driver is responsible for lateral control of the vehicle at all times.

III.A.11. If the front vehicle changes lanes, the rear driver shall do so as well if continued linking is desired. If not, the driver will have time (5-20 seconds) before the system automatically de-links and returns the vehicle to manual control.

## III.B. On Board System Requirements

### III.B.1. General

III.B.1. The DATP system shall support Class 8 tractor-trailer combinations.

III.B.2. The DATP system shall operate on limited access highways such as interstate highways and major US highways.

III.B.3. The DATP system shall operate across speed ranges for cruising speed typical on interstate highways and major US highways.

III.B.4. The DATP system shall operate in close formation platoon in a defined set of weather conditions (to be defined at a later stage in system development); operations shall be adjusted based on weather conditions as needed to maintain safety.

III.B.5. Any external indicators showing that the platooning system is active, if required, shall conform to any applicable state and federal laws.

III.B.6. All DATP systems shall be capable of operating as either the lead or the rear vehicle.

III.B.7. DATP system as a whole shall consume no more than 50 watts in electrical power.

III.B.8. The DATP system shall interface with the on-board J1939 databus.

III.B.9. The DATP system shall maintain a cellular data link to a central server for purposes of arranging link pairs.

### III.B.2. Sensing

III.B.10. DATP-equipped vehicles shall include the capability of forward collision mitigation.

III.B.11. The DATP system shall detect and track objects in the line of travel of the subject vehicle. These objects include a potential linking partner vehicle or other non-linking vehicles such as cars, SUV's, etc. Any vehicle that is in the subject vehicle's path of travel and acts as a potential collision threat shall be detected by the DATP system within 100 milliseconds.

III.B.12. The sensing field of view shall support typical interstate highway road curvature.

III.B.13. The DATP system in the rear vehicle shall precisely sense the position, range, and range rate of the lead vehicle.

III.B.14. The DATP sensing system shall provide accurate distance measurement in relation to the lead vehicle to within .3 meters of a vehicle in front of the target vehicle.

III.B.15. The DATP system shall use forward sensor range rate data to accurately measure the relative velocity between the two vehicles to within .15 m/s.

III.B.16. In the case of loss of satellite positioning data, the DATP system shall use the sensing subsystem to maintain spacing in relation to the lead vehicle for a sufficient time to safety separate the two vehicles while this condition persists. The amount of time depends on specific operating conditions.

### III.B.3. Positioning

III.B.17. The DATP system shall provide an accurate and smooth determination of relative positioning and speed between the two trucks. The DATP system shall provide accurate relative position data to within the nearest 10 centimeters (both longitudinal and lateral).

III.B.18. The DATP system shall provide elevation data accurate to X.XX meters.

III.B.19. Using satellite positioning data, velocity accuracy shall be within 0.1 miles per hour.

III.B.20. The DATP positioning subsystem shall provide data sufficient to discriminate between communications from in-lane vehicles, adjacent lane vehicles, and other vehicles.

III.B.21. In the case of loss of forward sensor data, the DATP system shall use the positioning subsystem to maintain position referencing in relation to the lead vehicle for a sufficient time to safety separate the two vehicles while this condition persists. The amount of time depends on specific operating conditions.

### III.B.4. Situational Awareness

III.B.22. The DATP system shall maintain awareness of both vehicles in the linked pair, as well as nearby vehicles and other objects relevant to system operation. This applies to both stationary and moving objects on the roadway.

III.B.23. Using on-board sensors, positioning data, and on-board data, the system shall combine road grade, engine torque level, transmission gear status, and vehicle descend and ascend information to estimate mass of the vehicle.

III.B.24. The mass of each vehicle shall be communicated to the vehicle pairing algorithm.

III.B.25. The estimated mass of the vehicle shall be used to estimate braking ability.

III.B.26. The system must be aware of braking application and degree on both loaded combination vehicles. The system must recognize braking applied on both trucks in platooning situations in order to maintain the target following distance during platooning operations.

III.B.27. The lead vehicle shall send engine torque to the rear vehicle.

III.B.28. Data from sensors, the positioning subsystem, and the on-board data bus shall be fused to increase the robustness of system operation overall.

### III.B.5. Maneuvering and Control

III.B.29. The DATP system shall be responsible for longitudinal control when activated (the driver shall be responsible for lateral control).

III.B.30. The DATP system shall control throttle position, engine torque, gear selection (for automated manual transmission vehicles), and braking including engine brakes/retarders as well as foundation brakes.

III.B.31. The DATP system shall allow the driver to control throttle, braking, gear selection, and steering at any time.

III.B.32. Based on estimated braking ability (based on all relevant factors), the vehicle with the better braking ability shall be designated as the rear vehicle.

III.B.33. The DATP system shall adapt to variances in braking capability between the two trucks and variation on each truck, in terms of defining the ordering of vehicles (leading, following) and in setting inter-vehicle spacing.

III.B.34. The inter-vehicle distance shall be a time headway of minimum X.XX seconds and maximum X.XX seconds. (The time headway and distance shall vary with speed selection.)

III.B.35. The DATP system shall use data from both vehicles to continually calculate optimum inter-vehicle distance to maintain a safe stopping distance in an emergency braking situation.

III.B.36. The DATP system shall modulate throttle and brakes of one or both vehicles to achieve the calculated safe inter-vehicle distance.

III.B.37. Braking on the rear truck shall be initiated within .05 seconds of brake initiation on the lead truck.

III.B.38. The DATP system should be aware of weather conditions.

III.B.39. The DATP system shall adjust operating parameters to respond to weather conditions that could affect braking distance. This could include separating the trucks up to a distance typical of manual driving.

III.B.40. The DATP system shall be able to safely respond to situations in which non-linked vehicles cut in between two linked vehicles. Such an occurrence shall be detected within 0.1 seconds of the cut-in vehicle being within the travel path of the target vehicle.

III.B.41. The rear vehicle in a DATP pair shall react up to and including full braking to avoid or mitigate a collision with any vehicle that intervenes between the linked pair.

*De-Linking and Re-Linking*

III.B.42. When de-linking is initiated, the driver shall be notified.

III.B.43. The delinking operation shall be smooth and predictable to the driver, providing sufficient time for the driver to retake full control of the vehicle.

III.B.44. Within the de-linking process, the vehicle shall maintain longitudinal control until the driver re-engages the throttle and /or brake.

III.B.45. De-linking shall occur based on:

a. Lead driver sending a de-link command to the system
b. Rear driver depressing the brake pedal
c. To be determined: rear driver depressing accelerator pedal
d. A non-linked vehicle cutting between the two linked vehicles
e. A system fault requiring de-linking
e. A change in environmental or traffic conditions requiring de-linking

III.B.46. In a lane change identified by the system as part of an evasive maneuver, the system shall automatically decelerate the rear vehicle and initiate de-linking.

Note: a criteria to define emergency lane change (possibly based on steering angle rate) is planned for development in Phase II if resources allow.

### III.B.6. Detection and Reaction to Faults

III.B.47. The J1939 bus of the truck will contain any faults from the stock ECUs of the truck. These include items such as emissions issues which can impose limits on torque production or otherwise impact the operation of the platooning system. These will be read directly from the J1939 bus, and conform to the standard. The system shall respond to faults in a manner to ensure safety.

III.B.48. Important mechanical faults shall also be detected, including some not detected by the existing ECUs on the truck. Critical faults are brake system issues, tire blowouts, and trailer disconnection.

III.B.49. DATP operation shall be disengaged or adjusted appropriately in the following conditions (which the system shall detect):

- Communications
  - J1939 Bus connection lost for more than .XX seconds
  - CAN (for radar) bus connection lost for more than .XX seconds
  - DSRC connection lost for more than .XX seconds
- Actuators
  - Engine torque interface failure
  - Brake system interface failure (including engine brake/retarder as well as the foundation brakes)

- Sensors
    - Radar fault
    - Accelerometer/IMU out of range
- Software:
    - ECU failure for processor running control algorithms
    - Software crash
- User Interface: loss of connection to and from the main ECU

III.B.50. The truck shall have additional diagnostics, including:

- Brake condition diagnostic: a diagnostic that examines the response to brake application to make sure that the brakes are in good condition.
- Engine braking diagnostic: examining the response of the truck to engine brake application to detect any issues with the engine brake subsystem.
- Engine torque production diagnostic: a diagnostic that looks at truck acceleration to detect a difference between the commanded engine torque and the actual engine torque.

### III.B.7. Human-Machine Interface

III.B.51. The DATP HMI system components within the driver compartment shall not act as a hindrance to the driver.

III.B.52. The interface screen shall be positioned in or near the view of the driver view, in compliance with state and federal regulations about equipment on the windshield.

III.B.53. The interface screen shall display information and facilitate driver selections.

III.B.54. When no loaded combinations are in DSRC range, the display shall show suggested trucks to link with (identified over cellular data connections).

III.B.55. A video display will show each driver the view from the other tractor's front perspective.

III.B.56. The video display must not block the driver's view or distract the driver from the driving task, and must be sufficiently bright to be easily visible during the day, and sufficiently dim in night and low light situations to not blind the driver.

III.B.57. Any system-induced changes to operational mode (such as delinking or fault handling) shall be indicated appropriately and be understandable to the driver; the driver's responsibilities in these cases (if any) shall be clearly indicated.

<u>Engaging the Link</u>

III.B.58. Once in position to link, the drivers (of both trucks) must affirmatively indicate to engage the link between the trucks. The design of this engagement selection and the resulting action shall be clear, intuitive, and ensure vehicle safety.

III.B.59. There shall be a means of indicating to both drivers which truck should be in front (based on braking ability).

III.B.60. Once a truck is in range, if the system is unavailable for linking the screen shall indicate the reason for the unavailability.

III.B.61. Once conditions are met (system booted up, speed appropriate, etc.), the screen shall displays a "ready to link" selection to the front driver.

III.B.62. Once the driver has indicated readiness to link, the rear driver shall be given the option to initiate the link.

Disengaging the Link

III.B.63. Access to a disengaging button must be present on the display at all stages of the platooning. There must also be a physical button available to the driver at all times to disengage the platooning.

III.B.64. When the link is disengaged, the reason for this will be displayed to the driver for a period of time.

III.B.65. Any system-induced changes to operational mode (such as delinking or fault handling) shall be indicated to the driver;

## III.C. Inter-Vehicle Communications System Requirements

III.C.1. The DATP system shall provide critical vehicle operational parameters between paired vehicles. The minimum parameters are:

- Braking status: deceleration, torque, and pressure
- Engine torque
- Acceleration/Deceleration in the longitudinal direction
- Location, vehicle velocity, and direction
- System status (truck and DATP system)
- Vehicle Size

III.C.2. Data shall be coded into messages consistent with applicable standards.

III.C.3. The inter-vehicle communications system shall continuously monitor the communication quality and reliability and provide this information to the system controller, such that a loss of communication is detected within 50ms.

III.C.4. The inter-vehicle communications system shall include one or more 5.9 GHz DSRC antennas installed so as to preserve line of sight between the vehicles when a trailer is attached.

III.C.5. The RF system shall handle antenna diversity as well as standard protocols to optimize robustness of communications.

III.C.6. Bandwidth of the communications channel shall be adequate to support continuous video streaming as well as data exchange.

III.C.7. The inter-vehicle communications system shall implement information security measures to prevent intentional disruption of or tampering with the communication link.

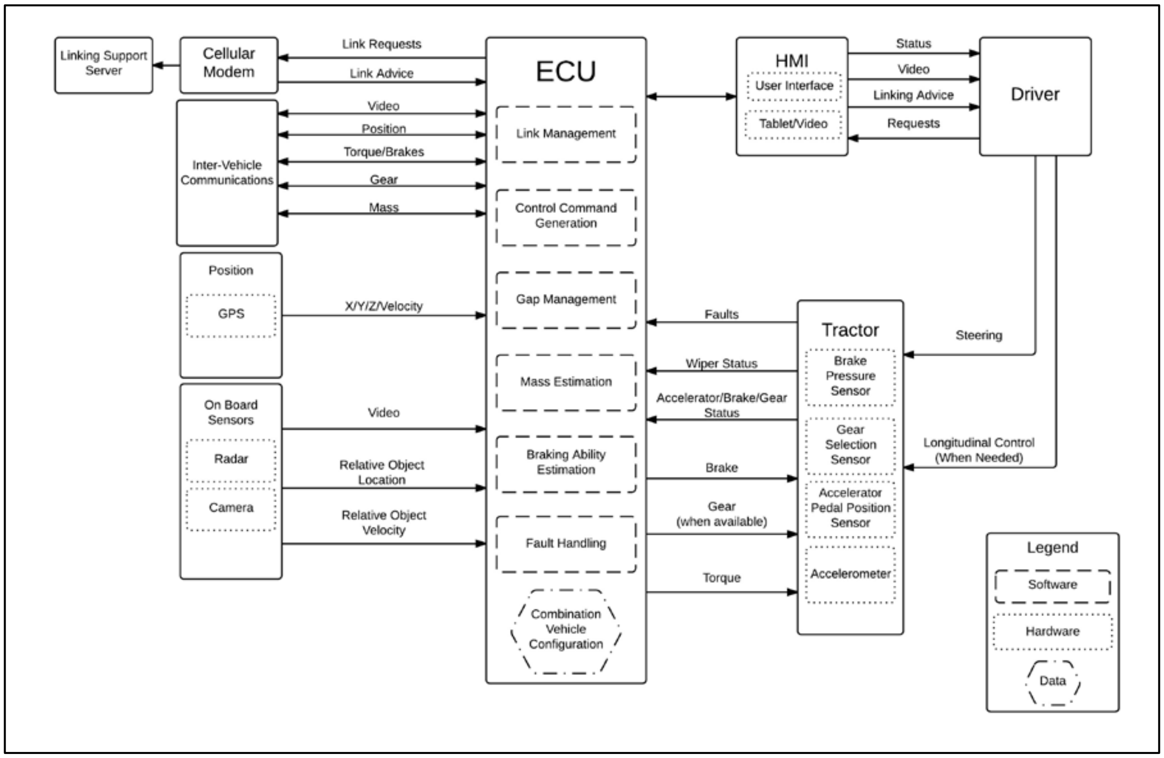


Figure 3: DATP Block Diagram

## IV. Conclusion

In this document, Driver Assistive Truck Platooning (DATP) has been elaborated as a concept and in terms of system requirements to guide Phase II work.

A wide range of operational issues are addressed, addressing drivers, fleet managers, dispatching, and more. Operations-oriented sections provide four operational scenarios plus user-oriented operational descriptions for drivers and fleet managers.

Technical discussions address the full breadth of the system, in areas such as sensing and computing hardware; driver interface; sensor and actuator software and interfacing; control software; diagnostics and reaction; truck systems, and operational environment.

Going forward, the project analyses and stakeholder outreach will expand upon the topics above with extensive interplay between the stakeholder input process, the analytical research focus, and on-track and on-road testing.

## B. DATP Trucking Industry Survey Results Summary

The following DATP section provides guidance on the users, sectors, and business models that are most likely to consider investing in DATP systems. In turn, it does not highlight and rationalize those industry markets that are least likely to consider DATP adoption.

The ATRI industry survey solicited both carrier and driver cost and benefit expectations. In general, the industry has high knowledge and understanding regarding standard technology and safety systems. However, the respondents had a limited basis for estimating the full scope of costs and benefits of DATP as described in this report. This creates challenges for the survey process, which should be viewed as an ***initial investigation*** that will be refined as stakeholders gain increased understanding through project activities. Nevertheless insights can be found from these early results that serve to guide the key question for this research project: what does it take for the trucking industry to embrace DATP?

To conduct the survey, a press release was issued through ATRI which detailed truck platooning research, and contained a link to the survey hosted on ATRI's website. This press release was emailed to the entirety of ATRI's industry contact list comprised of motor carriers, company drivers, owner-operators, state trucking association executives, and the like, representing the various sectors of the trucking industry.

**I. Overall Response Demographic (109 responses)**

- 37.6% of responses were owner-operator/independent contractors
- 40.4% of responses were company drivers
- 22.0% of responses were fleet management

**II. Owner-Operators/Independent Contractors**

- Mainly operate in the TL sector (64%), are traveling 500+ miles per trip (71%), have been driving for 7+ years (75%), and operate on limited access interstates and similar class highways with more than 2 lanes in the same direction (73%)
- 45% of the time they start early morning and end in the afternoon, 39% of the time they start late morning/afternoon and end in the evening, and 25% of the time they start in the evening and end the morning of the next day
- 75% of the time they are often traveling new routes or the routes are constantly changing
- 72% of the time the route is always planned before the trip, however when that is the case, 83% of the time the route changes while driving, and the driver is almost always the one who plans the route (87%) and is bound to that route only 10% of the time
- Approximately 25% of drivers have never heard of adaptive cruise control, and all drivers are familiar with collision warning, however only 19% have ever used it
- Drivers *willing to pay for the system* would be willing to pay (*Note: Averages and medians based on the 30% of owner-operators indicating a willingness to pay for the system; values such as $0 or $1 were excluded from calculations*):
    - An average of $1,511 (median of $850) to install the system,
    - An average of $497 (median of $500) a year to operate the system,
    - and would need an average break even period of 10 (median of 6) months.

- 79% would want the subscription to be structured per-month or per-year, however a majority (67%) would not be willing to pay for a subscription service
- When asked who they would platoon with:
  - 17% with other owner-operators (n=5)
  - 7% with any large fleet (n=2)
  - 10% specific fleet with whom they have already platooned (n=3)
  - 17% their own fleet's trucks (n=5)
  - 48% responded they would not use the system (n=14)
- 71% reported they would not be very willing or not willing at all to pay the lead truck in the platoon for fuel savings, and 95% reported they would not be very willing or not willing at to delay departure times for the opportunity to platoon
- The preferred method of training for the system would be a driving simulator while the least preferred would be system based self-training on the road
- 86% believe it will have a somewhat or very negative impact on driver retention, and 81% think drivers are unlikely or not likely at all to use the system

**III. Company Drivers**

- Mainly operate in the TL sector (65%), are traveling less than 500 miles per trip (57%), have been driving for 7+ years (79%), and operate on limited access interstates and similar class highways with more than 2 lanes in the same direction (83%)
- 59% of the time they start early morning and end in the afternoon, 40% of the time they start late morning/afternoon and end in the evening, and 23% of the time they start in the evening and end the morning of the next day
- 91% of the time they are often traveling the same routes or a mixture of the same routes and new routes
- 70% of the time the route is always planned before the trip, however when that is the case, 75% of the time the route changes while driving, and the route is planned by both the driver and carrier 66% and 42% of the time respectively. The driver is mostly or sometimes bound to that route 68% of the time
- Approximately 14% of drivers have never heard of adaptive cruise control, and all drivers are familiar with collision warning, and 36% have ever used it
- Drivers *willing to pay for the system* would be willing to pay(*Note: Averages and medians based on the 22% of company drivers indicating a willingness to pay for the system; values such as $0 or $1 were excluded from calculations*):
  - An average of $1,040 (median of $850) to install the system,
  - And average of $350 (median of 525) year to operate the system,
  - and would need an average break even period of 20 (median of 12) months.
- 88% would want the subscription to be structured per-month or per-year, however a majority (85%) would not be willing to pay for a subscription service
- When asked who they would platoon with:
  - 9% with other owner-operators (n=3)
  - 9% with any large fleet (n=3)
  - 19% specific fleet with whom they have already platooned (n=6)

    - 38% their own fleet’s trucks (n=12)
    - 25% responded they would not use the system (n=8)
- 50% reported they would not be very willing or not willing at all to pay the lead truck in the platoon for fuel savings, 18% reported they would be very or somewhat willing, and 32% had no opinion. 82% reported they would not be very willing or not willing at to delay departure times for the opportunity to platoon, while 9% said they would be somewhat willing.
- The preferred method of training for the system would be a driving simulator or an on-site driver training room, while the least preferred would be system based self-training on the road
- 68% believe it will have a somewhat or very negative impact on driver retention, and 87% think drivers are unlikely or not likely at all to use the system

**IV. Fleet Management**

- 62% operate for-hire while 31% are private carriers
- Spread fairly evenly throughout the sectors
    - 38% TL
    - 38% LTL
    - 25% Specialized
- Mainly operate in a 100-1000 mile range (78%), and operate on limited access interstates and similar class highways with more than 2 lanes in the same direction (71%)
- 56% of the time they start early morning and end in the afternoon, 23% of the time they start late morning/afternoon and end in the evening, and 27% of the time they start in the evening and end the morning of the next day
- 71% of the time they are often traveling the same routes or a mixture of the same routes and new routes
- 75% of the time the route is always planned before the trip, however when that is the case, 69% of the time the route changes while driving, and the route is planned by both the driver and carrier evenly. The driver is always or mostly bound to that route 69% of the time
- Only 8% of fleet managers have never heard of adaptive cruise control, however only 31% have every used it in any regard. All fleet managers are familiar with collision warning, however only 15% have ever used it
- Fleet managers would be willing to pay(*Note: Averages and medians based on the 75% of fleet managers indicating a willingness to pay for the system; values such as $0 or $1 were excluded from calculations*):
    - An average of $1,017 (median of $750) to install the system,
    - An average of $528 (median of $500) a year to operate the system,
    - and would need an average break even period of 18 (median of 18) months.
- 92% would want the subscription to be structured per-platooned-mile or per-month, and would want the subscription type to be as follows:
    - High install, lower subscription: 31%
    - Low install, higher subscription: 23%
    - Significantly higher install, no subscription: 39%
- When asked who they would platoon with:

- 5% with other owner-operators (n=1)
  - 27% with any large fleet (n=6)
  - 18% specific fleet with whom they have already platooned (n=4)
  - 46% their own fleet's trucks (n=10)
  - 5% responded they would not use the system (n=1)
- 39% reported they would not be very willing or not willing at all to pay the lead truck in the platoon for fuel savings, 31% reported they would be somewhat willing, and 31% had no opinion. 54% reported they would not be very willing or not willing at to delay departure times for the opportunity to platoon, while 23% said they would be somewhat willing.
- The preferred method of training for the system would be an on-site driver training room, while the least preferred would be system based self-training on the road
- 46% believe it will have a somewhat or very negative impact on driver retention, 15% very or somewhat positive, and 39% believe no impact.
- 62% think drivers are unlikely or not likely at all to use the system
  - 23% think drivers are very likely or likely to use the system
  - 15% think drivers are moderately likely to use the system
- Willingness to pay points cross-tabulated with fleet size:

| N | Fleet Size | WTP Install ($) | WTP Maintenance ($) | Break Even Period (months) |
|---|---|---|---|---|
| 0 | 0-6 | - | - | - |
| 1 | 7-20 | 1000 | 1000 | 1 |
| 2 | 21-50 | 750 | 400 | 18 |
| 5 | 51-500 | 1120 | 422 | 10.8 |
| 0 | 501-1000 | - | - | - |
| 1 | 1001-5000 | 2000 | 250 | 36 |
| 1 | 5001+ | 1000 | 250 | 36 |

**DATP Survey Results – Number of Responses for Each Question**

**A. Please select whether you are a:**

| Job Title | Number | Percentage |
|---|---|---|
| Owner-Operator/Independent Contractor | 41 | 37.6% |
| Company Driver | 44 | 40.4% |
| Fleet Management | 24 | 22.0% |
| Total | 109 | |

**I. Owner Operators**

1. Which of the following best describes you?

| Type | Number | Percent |
|---|---|---|
| Leased O-O/Independent Contractor | 13 | 59.1% |
| Owner-operator (O-O) with own authority | 9 | 40.9% |
| Total | 22 | |

2. Which sector of the trucking industry do you primarily operate in?

| Sector | Number | Percent |
|---|---|---|
| Truckload | 14 | 63.6% |
| Less –than-truckload | 2 | 9.1% |
| Specialized, flatbed | 1 | 4.5% |
| Specialized, tanker | 1 | 4.5% |
| Express/Parcel Service | 0 | 0.0% |
| Intermodal Drayage | 1 | 4.5% |
| Other (please specify) | 3 | 13.6% |
| Total | 22 | |

3. How many total power units does your fleet operate?

| Total Power Units | Number | Percent |
|---|---|---|
| 1-5 | 16 | 72.7% |
| 6-15 | 0 | 0.0% |
| 16-30 | 0 | 0.0% |
| 31-60 | 0 | 0.0% |
| 61-100 | 2 | 9.1% |
| 100+ | 4 | 18.2% |

| | | |
|---|---|---|
| Total | 22 | |

4. What is the primary truck configuration you operate?

| Truck Configuration | Number | Percent |
|---|---|---|
| 5-axle Dry Van | 9 | 42.9% |
| 5-axle Refrigerated Trailer | 4 | 19.0% |
| 5-axle Flatbed | 4 | 19.0% |
| 5-axle Tanker | 1 | 4.8% |
| Straight Truck | 1 | 4.8% |
| Longer Combination Vehicle (Double, Triple, etc.) | 1 | 4.8% |
| Other (please specify) | 1 | 4.8% |
| Total | 21 | |

5. What is your average length of haul?

| Average Length of Haul | Number | Percent |
|---|---|---|
| Local (less than 100 miles per trip) | 1 | 4.8% |
| Regional -Short/Line Haul (100-499 miles per trip) | 5 | 23.8% |
| Inter-regional (500-999 miles per trip) | 4 | 19.0% |
| Long- Haul (1000 or more miles per trip) | 11 | 52.4% |
| Total | 21 | |

6. How many years have you been driving professionally?

| Year Driving | Number | Percent |
|---|---|---|
| Less than 1 year | 0 | 0.0% |
| 1-3 years | 1 | 5.0% |
| 4-6 years | 4 | 20.0% |
| 7-15 years | 3 | 15.0% |
| More than 15 years | 12 | 60.0% |
| Total | 20 | |

7. On what type of roads do you typically operate?

| Road Type | Number of Responses |
|---|---|
| Limited-access Interstate and similar class highways, ≥ 3+ lanes in the same direction | 18 |
| Limited-access Interstate and similar class highways, 2 lanes in the same direction | 21 |

| | |
|---|---|
| Undivided rural highways, urban and suburban roads and streets | 20 |

8. Please indicate the departure/arrival times of a typical operation day.

| Departure/Arrival Times | Number of Responses |
|---|---|
| Start early morning and end in the afternoon | 21 |
| Start late morning/afternoon and end in the evening | 18 |
| Start in the evening and end next day in the morning | 18 |

9. How fixed are your routes?

| Fixed Route Status | Number of Responses |
|---|---|
| Often the same route every day for driver | 17 |
| Mixture of new routes and regular routes | 17 |
| Very mixed, often new routes | 15 |
| Constantly changing routes | 13 |

10. What is the route planning horizon?

| Route Planning Horizon | Number of Responses |
|---|---|
| Route always planned before trip | 20 |
| Sometimes change routes while driving | 16 |
| Often change routes while driving | 13 |
| Specific route is not planned in advance | 15 |

11. Who is responsible for route planning?

| Who Plans the Route? | Number of Responses |
|---|---|
| Driver | 21 |
| Carrier / Dispatcher | 11 |
| Other | 10 |

12. How frequently is the driver bound to the planned route?

| Driver Bound to Route | Number | Percent |
|---|---|---|
| Always | 2 | 9.5% |
| Mostly | 7 | 33.3% |
| Sometimes | 4 | 19.0% |

| | | |
|---|---|---|
| Rarely | 2 | 9.5% |
| Never | 6 | 28.6% |
| Total | 21 | |

13. How familiar are you with the use of truck adaptive cruise control (ACC)?

| How Familiar with ACC | Number | Percentage |
|---|---|---|
| Never heard of | 5 | 25.0% |
| Heard of | 6 | 30.0% |
| Seen | 2 | 10.0% |
| Used Once | 2 | 10.0% |
| Used infrequently | 2 | 10.0% |
| Used Frequently | 3 | 15.0% |
| Total | 20 | |

14. How familiar are you with the use of collision warning systems?

| How Familiar with Collision Warning | Number | Percentage |
|---|---|---|
| Never heard of | 0 | 0.0% |
| Heard of | 13 | 61.9% |
| Seen | 4 | 19.0% |
| Used Once | 1 | 4.8% |
| Used infrequently | 2 | 9.5% |
| Used Frequently | 1 | 4.8% |
| Total | 21 | |

15. Considering an estimated fuel saving of 5-10%, what is the maximum amount per truck you would be willing to pay to purchase this system?

- 8 responses

16. What is the maximum amount per truck you would be willing to pay to operate this system (per year)?

- 9 responses

17. What is the necessary payback / break-even time period you would need from this system?

- 6 responses

18. If a subscription based model were proposed for this system, which of the following would best suit you?

| Subscription Type | Number | Percentage |
|---|---|---|
| Higher hardware price, with lower subscription fee | 4 | 19.0% |
| Lower hardware price, with higher subscription fee | 1 | 4.8% |
| Significantly higher hardware price, with no subscription fee | 2 | 9.5% |
| Other (please specify) | 14 | 66.7% |
| Total | 21 | |

*Note: 'Other' write in responses were indicating the respondent would not use the system.

19. What subscription payment structure would you prefer most?

| Payment Structure | Number | Percentage |
|---|---|---|
| Per-platooned-hour | 0 | 0.0% |
| Per-platooned-mile | 3 | 21.4% |
| Per-month | 7 | 50.0% |
| Per-year | 4 | 28.6% |
| Total | 14 | |

20. When operating in the vicinity of other platoon-capable trucks, who would you be willing to platoon with? Check all that apply.

| Willing to Platoon | Number | Percentage |
|---|---|---|
| Other Owner-Operators | 5 | 17.2% |
| Any Large Fleet | 2 | 6.9% |
| Specific Fleets with whom you have already partnered | 3 | 10.3% |
| Your own fleet trucks | 5 | 17.2% |
| Other (please specify) | 14 | 48.3% |
| Total | 29 | |

*Note: 'Other' write in responses were indicating the respondent would not use the system.

21. If your truck is in a follower position and saving more energy than the leader truck, how willing would you be to pay a small fee (electronically) to the leader to compensate for part of the difference in energy saving (e.g., a percentage of fuel savings)? (Or, alternatively, to be paid a fee if your truck is in the lead).

| WTP Lead Driver | Number | Percent |
|---|---|---|
| Very willing | 2 | 9.5% |
| Somewhat willing | 2 | 9.5% |
| Neutral | 2 | 9.5% |
| Not very willing | 2 | 9.5% |
| Not willing at all | 13 | 61.9% |
| Total | 21 | |

22. With the assumption of 5-10% potential fuel savings and no additional constraints (hours of service or critical time delivery), how willing would you be to delay your departure time to facilitate platooning?

| Willing to Delay | Number | Percent |
|---|---|---|
| Very willing | 0 | 0.0% |
| Somewhat willing | 1 | 4.8% |
| Neutral | 0 | 0.0% |
| Not very willing | 5 | 23.8% |
| Not willing at all | 15 | 71.4% |
| Total | 21 | |

23. Please rank the following options on how drivers should be trained on this system (1 being most preferred, 5 being least preferred):

| | Number Ranked | | | | |
|---|---|---|---|---|---|
| **Training Type** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
| System based self-training on the road | 0 | 3 | 1 | 1 | 5 |
| On-site driver training room | 3 | 3 | 2 | 3 | 0 |
| On-line training | 2 | 0 | 5 | 2 | 3 |
| Driving simulator | 4 | 4 | 1 | 1 | 4 |
| Other | 4 | 0 | 0 | 1 | 4 |

24. What impact do you think truck platooning will have on driver retention?

| Driver Retention Impact | Number | Percentage |
|---|---|---|
| Very Positive | 0 | 0.0% |
| Somewhat Positive | 0 | 0.0% |
| No Impact | 3 | 14.3% |
| Somewhat Negative | 4 | 19.0% |
| Very Negative | 14 | 66.7% |
| Total | 21 | |

25. How likely do you think drivers are to want to use the technology?

| Likeliness to Use | Number | Percentage |
|---|---|---|
| Very Likely | 0 | 0.0% |
| Likely | 1 | 4.8% |
| Moderately likely | 3 | 14.3% |
| Unlikely | 4 | 19.0% |
| Not likely at all | 13 | 61.9% |
| Total | 21 | |

**II. Company Drivers**

1. Which sector of the trucking industry do you primarily operate in?

| Sector | Number | Percent |
|---|---|---|
| Truckload | 13 | 65.0% |
| Less –than-truckload | 0 | 0.0% |
| Specialized, flatbed | 1 | 5.0% |
| Specialized, tanker | 5 | 25.0% |
| Express/Parcel Service | 0 | 0.0% |
| Intermodal Drayage | 0 | 0.0% |
| Other (please specify) | 1 | 5.0% |
| Total | 20 | |

2. How many total power units does your fleet operates?

| Total Power Units | Number | Percent |
|---|---|---|
| 0-6 | 2 | 8.3% |
| 6-20 | 2 | 8.3% |
| 21-50 | 1 | 4.2% |
| 51-500 | 10 | 41.7% |
| 501-1000 | 3 | 12.5% |
| 1001-5000 | 4 | 16.7% |
| 5001+ | 2 | 8.3% |
| Total | 24 | |

3. What is the primary truck configuration you operate?

| Truck Configuration | Number | Percent |
|---|---|---|
| 5-axle Dry Van | 8 | 33.3% |
| 5-axle Refrigerated Trailer | 5 | 20.8% |
| 5-axle Flatbed | 1 | 4.2% |
| 5-axle Tanker | 6 | 25.0% |
| Straight Truck | 0 | 0.0% |
| Longer Combination Vehicle (Double, Triple, etc.) | 2 | 8.3% |
| Other (please specify) | 2 | 8.3% |
| Total | 24 | |

4. What is your average length of haul?

| Average Length of Haul | Number | Percent |
|---|---|---|
| Local (less than 100 miles per trip) | 2 | 8.3% |
| Regional -Short/Line Haul (100-499 miles per trip) | 11 | 45.8% |

| | | |
|---|---|---|
| Inter-regional (500-999 miles per trip) | 6 | 25.0% |
| Long- Haul (1000 or more miles per trip) | 5 | 20.8% |
| Total | 24 | |

5. How many years have you been driving professionally?

| Year Driving | Number | Percent |
|---|---|---|
| Less than 1 year | 0 | 0.0% |
| 1-3 years | 1 | 4.2% |
| 4-6 years | 4 | 16.7% |
| 7-15 years | 5 | 20.8% |
| More than 15 years | 14 | 58.3% |
| Total | 24 | |

6. On what type of roads do you typically operate?

| Road Type | Number of Responses |
|---|---|
| Limited-access Interstate and similar class highways, ≥ 3+ lanes in the same direction | 22 |
| Limited-access Interstate and similar class highways, 2 lanes in the same direction | 24 |
| Undivided rural highways, urban and suburban roads and streets | 24 |

7. Please indicate the departure/arrival times of a typical operation day.

| Departure/Arrival Times | Number of Responses |
|---|---|
| Start early morning and end in the afternoon | 20 |
| Start late morning/afternoon and end in the evening | 22 |
| Start in the evening and end next day in the morning | 19 |

8. How fixed are your routes?

| Fixed Route Status | Number of Responses |
|---|---|
| Often the same route every day for driver | 17 |

| | |
|---|---|
| Mixture of new routes and regular routes | 20 |
| Very mixed, often new routes | 16 |
| Constantly changing routes | 18 |

9. What is the route planning horizon?

| Route Planning Horizon | Number of Responses |
|---|---|
| Route always planned before trip | 22 |
| Sometimes change routes while driving | 18 |
| Often change routes while driving | 16 |
| Specific route is not planned in advance | 14 |

10. Who is responsible for route planning?

| Who Plans the Route? | Number of Responses |
|---|---|
| Driver | 22 |
| Carrier / Dispatcher | 17 |
| Other | 12 |

11. How frequently are you bound to the planned route?

| Driver Bound to Route | Number | Percent |
|---|---|---|
| Always | 0 | 0.0% |
| Mostly | 10 | 45.5% |
| Sometimes | 5 | 22.7% |
| Rarely | 2 | 9.1% |
| Never | 5 | 22.7% |
| Total | 22 | |

12. How familiar are you with the use of truck adaptive cruise control (ACC)?

| How Familiar with ACC | Number | Percentage |
|---|---|---|
| Never heard of | 3 | 13.6% |
| Heard of | 12 | 54.5% |
| Seen | 1 | 4.5% |
| Used Once | 0 | 0.0% |
| Used infrequently | 1 | 4.5% |
| Used Frequently | 5 | 22.7% |
| Total | 22 | |

13. How familiar are you with the use of collision warning systems?

| How Familiar with Collision Warning | Number | Percentage |
|---|---|---|
| Never heard of | 1 | 4.5% |
| Heard of | 11 | 50.0% |

| | | |
|---|---|---|
| Seen | 2 | 9.1% |
| Used Once | 2 | 9.1% |
| Used infrequently | 2 | 9.1% |
| Used Frequently | 4 | 18.2% |
| Total | 22 | |

14. Considering an estimated fuel saving of 5-10%, what is the maximum amount per truck you would be willing to pay to purchase this system?

- 4 responses

15. What is the maximum amount per truck you would be willing to pay to operate this system (per year)?

- 2 responses

16. What is the necessary payback / break-even time period you would need from this system?

- 5 responses

17. If a subscription based model were proposed for this system, which of the following would best suit you?

| Subscription Type | Number | Percentage |
|---|---|---|
| Higher hardware price, with lower subscription fee | 2 | 10.0% |
| Lower hardware price, with higher subscription fee | 1 | 5.0% |
| Significantly higher hardware price, with no subscription fee | 8 | 40.0% |
| Other (please specify) | 9 | 45.0% |
| Total | 20 | |

*Note: 'Other' write in responses were indicating the respondent would not use the system.

18. What subscription payment structure would you prefer most?

| Payment Structure | Number | Percentage |
|---|---|---|
| Per-platooned-hour | 1 | 5.9% |
| Per-platooned-mile | 1 | 5.9% |
| Per-month | 5 | 29.4% |
| Per-year | 10 | 58.8% |
| Total | 17 | |

19. When operating in the vicinity of other platoon-capable trucks, who would you be willing to platoon with? Check all that apply.

| Willing to Platoon | Number | Percentage |
|---|---|---|
| Other Owner-Operators | 3 | 9.4% |
| Any Large Fleet | 3 | 9.4% |
| Specific Fleets with whom you have already partnered | 6 | 18.8% |

| | | |
|---|---|---|
| Your own fleet trucks | 12 | 37.5% |
| Other (please specify) | 8 | 25.0% |
| Total | 32 | |

*Note: 'Other' write in responses were indicating the respondent would not use the system.

20. If your truck is in a follower position and saving more energy than the leader truck, how willing would you be to pay a small fee (electronically) to the leader to compensate for part of the difference in energy saving (e.g., a percentage of fuel savings)? (Or, alternatively, to be paid a fee if your truck is in the lead).

| WTP Lead Driver | Number | Percent |
|---|---|---|
| Very willing | 1 | 4.5% |
| Somewhat willing | 3 | 13.6% |
| Neutral | 7 | 31.8% |
| Not very willing | 3 | 13.6% |
| Not willing at all | 8 | 36.4% |
| Total | 22 | |

21. With the assumption of 5-10% potential fuel savings and no additional constraints (hours of service or critical time delivery), how willing would you be to delay your departure time to facilitate platooning?

| Willing to Delay | Number | Percent |
|---|---|---|
| Very willing | 0 | 0.0% |
| Somewhat willing | 2 | 9.1% |
| Neutral | 1 | 4.5% |
| Not very willing | 2 | 9.1% |
| Not willing at all | 16 | 72.7% |
| Total | 21 | |

22. Please rank the following options on how drivers should be trained on this system (1 being most preferred, 5 being least preferred):

| Training Type | 1st | 2nd | 3rd | 4th | 5th |
|---|---|---|---|---|---|
| System based self-training on the road | 3 | 3 | 2 | 2 | 7 |
| On-site driver training room | 5 | 3 | 4 | 3 | 0 |
| On-line training | 0 | 3 | 5 | 4 | 1 |
| Driving simulator | 6 | 3 | 4 | 1 | 1 |
| Other | 4 | 0 | 2 | 1 | 6 |

23. What impact do you think truck platooning will have on driver retention?

| Driver Retention Impact | Number | Percentage |
|---|---|---|
| Very Positive | 0 | 0.0% |
| Somewhat Positive | 2 | 9.1% |
| No Impact | 5 | 22.7% |
| Somewhat Negative | 6 | 27.3% |
| Very Negative | 9 | 40.9% |
| Total | 22 | |

24. How likely do you think drivers are to want to use the technology?

| Likeliness to Use | Number | Percentage |
|---|---|---|
| Very Likely | 0 | 0.0% |
| Likely | 0 | 0.0% |
| Moderately likely | 3 | 13.0% |
| Unlikely | 9 | 39.1% |
| Not likely at all | 11 | 47.8% |
| Total | 23 | |

**III. Fleet Management**

1. Which sector of the trucking industry do you operate in? (check one)

| Sector | Number | Percentage |
|---|---|---|
| For-hire | 8 | 61.5% |
| Private | 4 | 30.8% |
| Other (please specify) | 1 | 7.7% |
| Total | 13 | |

2. If you operate in the for-hire sector, what is your primary type of business? (check one)

| Sector | Number | Percentage |
|---|---|---|
| Truckload | 3 | 37.5% |
| Less-than-truckload | 3 | 37.5% |
| Specialized | 2 | 25.0% |
| Total | 8 | |

3. How many total power units does your fleet operates?

| Total Power Units | Number | Percent |
|---|---|---|
| 0-6 | 1 | 7.7% |
| 6-20 | 1 | 7.7% |
| 21-50 | 2 | 15.4% |
| 51-500 | 6 | 46.2% |
| 501-1000 | 0 | 0.0% |
| 1001-5000 | 1 | 7.7% |
| 5001+ | 2 | 15.4% |
| Total | 13 | |

4. What is the primary truck configuration you operate?

| Truck Configuration | Number | Percent |
|---|---|---|
| 5-axle Dry Van | 4 | 30.8% |
| 5-axle Refrigerated Trailer | 1 | 7.7% |
| 5-axle Flatbed | 2 | 15.4% |
| 5-axle Tanker | 0 | 0.0% |
| Straight Truck | 2 | 15.4% |
| Longer Combination Vehicle (Double, Triple, etc.) | 2 | 15.4% |
| Other (please specify) | 2 | 15.4% |
| Total | 13 | |

5. What is your average length of haul?

| Average Length of Haul | Number | Percent |
|---|---|---|
| Local (less than 100 miles per trip) | 2 | 15.4% |
| Regional -Short/Line Haul (100-499 miles per trip) | 7 | 53.8% |
| Inter-regional (500-999 miles per trip) | 3 | 23.1% |
| Long- Haul (1000 or more miles per trip) | 1 | 7.7% |
| Total | 13 | |

6. On what type of roads do you typically operate?

| Road Type | Number of Responses |
|---|---|

| | |
|---|---|
| Limited-access Interstate and similar class highways, ≥ 3+ lanes in the same direction | 13 |
| Limited-access Interstate and similar class highways, 2 lanes in the same direction | 13 |
| Undivided rural highways, urban and suburban roads and streets | 13 |

7. Please indicate the departure/arrival times of a typical operation day.

| Departure/Arrival Times | Number of Reponses |
|---|---|
| Start early morning and end in the afternoon | 13 |
| Start late morning/afternoon and end in the evening | 11 |
| Start in the evening and end next day in the morning | 12 |

8. How fixed are your routes?

| Fixed Route Status | Number of Responses |
|---|---|
| Often the same route every day for driver | 8 |
| Mixture of new routes and regular routes | 12 |
| Very mixed, often new routes | 6 |
| Constantly changing routes | 6 |

9. What is the route planning horizon?

| Route Planning Horizon | Number of Responses |
|---|---|
| Route always planned before trip | 12 |
| Sometimes change routes while driving | 10 |
| Often change routes while driving | 4 |
| Specific route is not planned in advance | 4 |

10. Who is responsible for route planning?

| Who Plans the Route? | Number of Responses |
|---|---|
| Driver | 10.0 |

| | |
|---|---|
| Carrier / Dispatcher | 10.0 |
| Other | 2.0 |

11. How frequently is the driver bound to the planned route?

| Driver Bound to Route | Number | Percent |
|---|---|---|
| Always | 2 | 15.4% |
| Mostly | 7 | 53.8% |
| Sometimes | 1 | 7.7% |
| Rarely | 1 | 7.7% |
| Never | 2 | 15.4% |
| Total | 13 | |

12. How familiar are you with the use of truck adaptive cruise control (ACC)?

| How Familiar with ACC | Number | Percentage |
|---|---|---|
| Never heard of | 1 | 7.7% |
| Heard of | 5 | 38.5% |
| Seen | 3 | 23.1% |
| Used Once | 1 | 7.7% |
| Used infrequently | 2 | 15.4% |
| Used Frequently | 1 | 7.7% |
| Total | 13 | |

13. How familiar are you with the use of collision warning systems?

| How Familiar with Collision Warning | Number | Percentage |
|---|---|---|
| Never heard of | 0 | 0.0% |
| Heard of | 6 | 46.2% |
| Seen | 5 | 38.5% |
| Used Once | 1 | 7.7% |
| Used infrequently | 1 | 7.7% |
| Used Frequently | 0 | 0.0% |
| Total | 13 | |

14. Considering an estimated fuel saving of 5-10%, what is the maximum amount you would be willing to pay to purchase this system?

- 6 responses

15. What is the maximum amount you would be willing to pay to operate this system (per year)?

- 7 responses

16. What is the necessary payback / break-even time period you would need from this system?

- 7 responses

17. If a subscription based model were proposed for this system, which of the following would best suit you?

| **Subscription Type** | **Number** | **Percentage** |
|---|---|---|
| Higher hardware price, with lower subscription fee | 4 | 30.8% |
| Lower hardware price, with higher subscription fee | 3 | 23.1% |
| Significantly higher hardware price, with no subscription fee | 5 | 38.5% |
| Other (please specify) | 1 | 7.7% |
| Total | 13 | |

*Note: 'Other' write in responses were indicating the respondent would not use the system.

18. What subscription payment structure do you prefer most?

| **Payment Structure** | **Number** | **Percentage** |
|---|---|---|
| Per-platooned-hour | 1 | 8.3% |
| Per-platooned-mile | 6 | 50.0% |
| Per-month | 5 | 41.7% |
| Per-year | 0 | 0.0% |
| Total | 12 | |

19. When operating in the vicinity of other platoon-capable trucks, who would you be willing to platoon with? Check all that apply?

| **Willing to Platoon** | **Number** | **Percentage** |
|---|---|---|
| Other Owner-Operators | 1 | 4.5% |
| Any Large Fleet | 6 | 27.3% |
| Specific Fleets with whom you have already partnered | 4 | 18.2% |
| Your own fleet trucks | 10 | 45.5% |
| Other (please specify) | 1 | 4.5% |
| Total | 22 | |

*Note: 'Other' write in responses were indicating the respondent would not use the system.

20. If your truck is in a follower position and saving more energy than the leader truck, how willing would you be to pay a small fee (electronically) to the leader to compensate for part of the difference in energy saving (e.g., a percentage of fuel savings)? (Or, alternatively, to be paid a fee if your truck is in the lead).

| WTP Lead Driver | Number | Percent |
|---|---|---|
| Very willing | 0 | 0.0% |
| Somewhat willing | 4 | 30.8% |
| Neutral | 4 | 30.8% |
| Not very willing | 3 | 23.1% |
| Not willing at all | 2 | 15.4% |
| Total | 13 | |

21. With the assumption of 5-10% potential fuel savings and no additional constraints (hours of service or critical time delivery), how willing would you be to delay your departure time to facilitate platooning?

| Willing to Delay | Number | Percent |
|---|---|---|
| Very willing | 0 | 0.0% |
| Somewhat willing | 3 | 23.1% |
| Neutral | 3 | 23.1% |
| Not very willing | 4 | 30.8% |
| Not willing at all | 3 | 23.1% |
| Total | 13 | |

22. Please rank the following options on how drivers should be trained on this system (1 being most preferred, 5 being least preferred):

| | Number Ranked | | | | |
|---|---|---|---|---|---|
| **Training Type** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
| System based self-training on the road | 1 | 1 | 4 | 2 | 4 |
| On-site driver training room | 5 | 5 | 2 | 0 | 0 |
| On-line training | 2 | 1 | 2 | 4 | 1 |
| Driving simulator | 2 | 2 | 1 | 3 | 2 |
| Other | 1 | 0 | 1 | 0 | 3 |

23. What impact do you think truck platooning will have on driver retention?

| Driver Retention Impact | Number | Percentage |
|---|---|---|
| Very Positive | 1 | 7.7% |

| | | |
|---|---|---|
| Somewhat Positive | 1 | 7.7% |
| No Impact | 5 | 38.5% |
| Somewhat Negative | 5 | 38.5% |
| Very Negative | 1 | 7.7% |
| Total | 13 | |

24. How likely do you think drivers are to want to use the technology?

| **Likeliness to Use** | **Number** | **Percentage** |
|---|---|---|
| Very Likely | 2 | 15.4% |
| Likely | 1 | 7.7% |
| Moderately likely | 2 | 15.4% |
| Unlikely | 7 | 53.8% |
| Not likely at all | 1 | 7.7% |
| Total | 13 | |