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Commercial Truck Platooning Demonstration in Texas – Level 2 Automation

Technical Report 0-6836-1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Beverly T. Kuhn, P.E., TX #80308.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER 1: PROJECT OVERVIEW

BACKGROUND

Through this project, the Texas Department of Transportation (TxDOT) funded the creation of a comprehensive truck platooning demonstration in Texas, serving as a proactive effort in assessing innovative operational strategies to position TxDOT as a leader in this research area and the overall transportation systems management and operation and connected vehicle and automated vehicle (CV/AV) initiatives. The focus was on the feasibility of deploying truck platoons with two or more vehicles on specific corridors in Texas within 5 to 10 years. The project brought together major partners, including government agencies, national labs, truck manufacturers and equipment suppliers, all of which have committed resources in terms of in-kind matching of equipment, engineering services, and intellectual property.

REASONS FOR AUTOMATION

The U.S. economy depends on the movement of goods within and across its borders with the transport of billions of tons of goods valued at tens of trillions of dollars being transported each year. Trucking comprises the majority of freight market. While trucks account for only 6 percent of the miles traveled in urban areas, they account for 26 percent of the total cost of congestion as measured in delay and wasted fuel. These annual costs top $23 billion. A significant conclusion of the Texas A&M Transportation Institute's (TTI) Urban Mobility Scorecard is that congestion effects extend far beyond a region where congestion occurs (*1*). Additionally, trucks are a key element in the just-in-time (or lean) manufacturing process, which uses efficient delivery timing of components to reduce the amount of inventory warehouse space. As a consequence, trucks become mobile warehouses. If arrival times are missed due to congestions, the combination of production and delivery delay costs will be many times the value of the truck delay times and this significant will be eventually passed to the end user.

Safety

Accidents in the trucking industry result in $19B in damage, lost goods, lost driver time, etc. These accidents also result in 5000 deaths each year. The Federal Motor Carrier Safety Administration (FMCSA) introduced in the Compliance, Safety, Accountability (CSA) scoring system to track the safety records of drivers. In the interest of safety, the CSA program provides a disincentive to hire drivers with lower scores, but has the unintended consequence of increasing costs to fleet managers and reducing the available pool of drivers. Improved safety could potentially allow drivers and the fleets they serve to achieve higher CSA scores.

Fuel Consumption

In 2009, United States heavy trucks consumed 44 billion gallons of fuel (18 percent of the U.S. total) and produced 500 million tons of CO_2. To put it another way, the average line haul trucker spends $70,000 per year on fuel, his/her single largest expense. Significant research funding has been spent developing and evaluating semi-automated convoy technologies that reduce both fuel consumption and CO_2 output. Programs such as Safe Road Trains for the Environment (SARTRE) and the Development of Energy-saving intelligent transportation system (ITS) Technology (Energy ITS) project have demonstrated 20 percent and 15 percent fuel economy improvement, respectively (*2*, *3*).

Driver Shortage

The American Trucking Association estimates that there is a truck driver shortage of 20,000–25,000. If trends continue this number could rise to 239,000 by the end of the decade. Retirements in the baby boomer generation and the impact of CSA scores have contributed to a lack of qualified drivers, leading to the challenges of driver retention, competitiveness of drivers' pay, and the increased cost of recruiting qualified drivers.

Federal rules governing commercial driver hours-of-service have increasingly become a major concern for the trucking industry. The proposed changes—decreasing driving and on-duty times and extending the restart provision—are problematic for the industry.

AV technologies are expected to make drivers more productive and safer while reducing fatigue. They can augment the activities of the driver similar to the way autopilot and auto-landing systems in the commercial aviation industry. The improvements could also allow for more favorable hours-of-service rules as the technology is proven.

PLATOONING AND THE RESPONSE TO THE RFP

Truck platooning—within the context of this research report—is an extension of cooperative adaptive cruise control (CACC) that realizes automated lateral and longitudinal vehicle control while moving in tight formation with short following distances. In addition to the feedback loop used in the platooning, which uses radar or LIDAR measurements to derive the range to the vehicle in front, the preceding vehicle's acceleration is used in a feed-forward loop. The preceding vehicle's acceleration is obtained from the basic safety messages it transmits using dedicated short-range communication (DSRC) and WAVE communication (*4*). These messages are transmitted 10 times per second (10 Hz) by vehicles equipped with DSRC radios (*5*). The platoon master controller controls the speed and lateral position using electronic throttle control, brake by wire, and electronic power assisted steering.

The platoon controller reflects an operational environment in which platoon-related decisions are made within the vehicles themselves and potentially supplemented by external information. This approach was taken because vehicle-based decision-making would be sufficient to organize and coordinate vehicles effectively within a local platoon, but platoon-level speed recommendations and advisories could come from an external entity (such as a traffic management center) that has visibility into the conditions of the entire road network.

It is valuable to investigate the potential of heavy vehicle platooning to significantly increase safety and reduce the cost of every mile traveled, while increasing the use of vehicle-to-vehicle (V2V) communication. The research team believes that supporting platooning technology is ready for commercialization and that it provides value in specific roadway, fleet, and operating conditions. While these benefits are established through various research projects, platoons must be placed into a real-world setting to assess practicality and return on investment (ROI).

Technology is only useful if it meets user needs. While research projects have shown platooning to have significant potential for fuel economy savings, operating platoons must be placed into a real-world setting to assess practicality and ROI.

The hypothesis of the research team is that platooning technology is ready for industrial use and will provide value in specific roadway and operating conditions for heavy truck fleet operations. Research is needed 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 platooning and to answer those questions. These questions must address industry needs and the needs of other highway travelers relating to traffic flow and safety. This work should lead to new levels of freight/fleet efficiency and improved mobility for all highway travelers, while substantially improving the trucking-based emissions picture and enhancing the V2V communications environment.

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 the American Transportation Research Institute 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 percent of large trucks now using telematics devices. Platooning research is critical to expanding these opportunities: government sponsorship of such research provides several important inputs, including seed funding, competition-neutral transparency, and public-private sector solutions and partnerships.

BENEFITS OF TRUCK AUTOMATION

Platooning is a near-term form of automation that can evolve to full-automation. However, it is also worthwhile to examine the longer term benefits of automation for trucks. The benefits of truck automation can be categorized in three dimensions: benefits to infrastructure providers, benefits for truck drivers, and economic benefits for commercial vehicle operators (*6*). Additionally, other indirect benefits may include improved quality of life or improved air quality due to reduced congestion.

Infrastructure providers concerned about traffic flow and congestion, public safety, roadway maintenance, and other operating expenses may also benefit from automation. Such benefits might include:

- Lane widths could be optimized for the different vehicle classes.
- Collisions between trucks and cars could be greatly reduced through reduction in driver-related crashes.
- Separate lanes could be operated at different speeds for different vehicle classes.
- Roadway structures and pavement design could be optimized for the different classes of vehicles.

The economic benefits for commercial vehicle operators might be substantial, and these potential benefits have been part of the transportation dialogue since 2001. As noted by Shladover, heavy truck costs and usage make the economic return of an investment in automation equipment significantly more attractive for a truck than for a passenger car (*7*). Additionally, the installation of automation equipment on a commercial truck is likely to be easier than on a car. Such factors as less constrained space for equipment, smaller order quantities, shorter lead time from design to production, the use of a standardized communications network, and other electronic engine and brake controls make heavy trucks more attractive for automation (*3*). Furthermore, automated trucks could result in significant changes in driving duty cycles and pay rates for drivers. For example, when trucks are fully automated, drivers could travel long distances while resting and still earn payment (*3*), and some current problems with driver fatigue and duty hours that conflict with sleep cycles might be solved with automation.

EXISTING PLATOONING EFFORTS

Many countries and regions across the world have realized and acknowledge the benefits of truck automation (i.e., CACC and platooning) and the impact it could have on improving operations, costs, and other factors discussed before. The following sections provide a descriptive list of major efforts in on this topic. Table 1 compares the worldwide platooning efforts.

Table 1. Comparison Table of Platooning Efforts across the World.

Project	Vehicle Type	Control	Infrastructure Req.	Traffic Integration	Sensors	Goals
SARTRE	Mixed	Lat. + Long.	None	Highway, Mixed	Production	Comfort, safety, congestion, energy
PATH	Cars or heavy trucks	Lat. + Long.	Reference markers in the road	Dedicated lane	Mixed	Increased throughput, energy saving
GCDC	Mixed	Long.	Augmented GPS	Mixed	State of the Art (SoA) and Production	Accelerate deployment
Energy-ITS	Heavy Trucks	Lat. + Long.	Lane Markings	Dedicated lane	SoA	Energy saving, mitigate lack of skilled drivers
COMPANION	Heavy Trucks	Long.	None	Highway, Mixed	No V2V comm. in 1st stage	Commercial fleet, energy
AMAS	Heavy Trucks	Lat. + Long.	None	Off-road	Production	Increased safety
Auburn	Heavy Trucks	Lat.	n/a	Highway, Mixed	Production	Energy Saving, safety

Europe

PROMOTE CHAUFFEUR (1996–2003 / > €5 million)

CHAUFFEUR project had performed perhaps the most extensive truck-platoon technology development and testing so far. This project was aimed at proving the feasibility of platooning technology and an initial demonstration of the concept (*8*).

KONVOI (2005–2009 / €5.5 million)

The study sponsored by Germany's Federal Ministry of Economics and Technology (not transport) examined the impacts that a truck-platooning system could have on traffic flow, fuel consumption, and the environment. The main objective was designed to evaluate how a truck platoon system could operate in practice on public roads. The target concept for KONVOI is of a platoon of up to four trucks that would drive in mixed traffic on the highway, with the driver of the first truck making the strategic maneuvering decisions for the platoon (*9*).

GCDC (2011)

In the 2011 Grand Cooperative Driving Challenge (GCDC), a number of vehicles cooperated in platoons in both urban and highway driving scenarios. The aim of the 2011 GCDC was to accelerate the development, integration, demonstration, and deployment of cooperative driving systems, based on the combination of V2V and vehicle-to-infrastructure (V2I) communication infrastructures and the state-of-the-art of sensor fusion and control. The challenge was to demonstrate how traffic shockwaves can be attenuated and to increase the road throughput (*10*).

SARTRE (2009–2012 / €6.4 million)

Funded through the European Commission's Seventh Research Framework Program, SARTRE is yet the most advanced demonstration of platooning by combination passenger vehicles and trucks while designing functional human-machine interfaces (HMI) and back-end infrastructure to monetize the platooning application beyond the obvious fuel savings and safety gains for fleet operators. A few safety requirements were implemented with this project. One of them is identified by the preliminary hazard analysis and states that a minimum safe distance must exist between vehicles. This would help prevent hazards such as the case in which higher than required acceleration might cause a collision between platooning vehicles. Multiple safety measures are suggested to ensure occupant safety. As an example, the possibility for a direct driver intervention of a follower vehicle is strongly recommended in case of vehicle autonomous unwanted behavior. This will allow the driver to accelerate, brake, steer, or press an emergency stop button, which will deactivate the vehicle from being controlled (*2*).

COMPANION (2014–2017 / €5.4 million)

The main focus of the project is how a single vehicle operating in a platoon should be efficiently controlled without jeopardizing safety. Longitudinal movement is automatically controlled while lateral movement is manual. The control architecture has been developed based on distributed control, meaning that each vehicle is responsible for its own control based on information from onboard sensors like radar, cameras, etc., and information exchange between the vehicles in the platoon via V2V communication (*11*).

United States

University of California at Berkeley Platooning of Trucks/Buses (1993–11 / n/a)

The Partners for Advanced Transportation Technology (PATH) first tested the longitudinal control of a four-car platoon at 4 m separation at highway speeds in 1994, and then developed the eight-car automated platoon for the National Automated Highway System Consortium Demo '97. More recently, the PATH platooning research has focused on heavy trucks, mainly because of the potential for energy saving associated with aerodynamic drag reductions. Operating tractor-trailer trucks in close-formation automated platoons of three trucks could enable a capacity of about 1500 trucks per lane per hour, which is twice the capacity achievable with trucks driven individually. The PATH experiments on truck platoons have shown the technical feasibility of driving two trucks at a gap of 3 m (9.8 ft) and three trucks at a gap of 4 m (13.1 ft) between trucks. The Metropolitan Transit Authority of Harris County, Texas, (Houston Metro) was the only transit authority participating in Demo '97. Houston Metro provided two New Flyer, 12.2 m) (40-ft) low-floor buses to participate in the demonstration runs. The buses were outfitted at Carnegie-Mellon University with the hardware and software necessary to be full automated. Houston Metro identified automated highway technology as having potential for future application to the Houston high occupancy vehicle (HOV) lane network as a cost-effective means of increasing vehicle throughput, and autonomous haulage system was to be specifically considered in Metro's long-range transportation plan. Houston Metro sought to be among the international leaders in the use of advanced technology to improve transportation. A study of crash safety was completed using modeling and simulation, which showed the advantages of a platoon rather than individual AVs. For platoons that have a high total probability of collisions, it is expected the severity is low. Although the probability for low cooperative individual vehicles is low, the collisions that occur are much more severe. The PATH research stated, "The gaps between platoons would be long enough to ensure that even in the worst crash hazard condition, with maximum deceleration; a following platoon would be able to stop without hitting the last vehicle of the forward platoon" (*12*).

U.S. Army CAST (2008–2010 / n/a)

The Convoy Active Safety Technology (CAST) development program sought to develop a low cost, optionally manned vehicle solution. An objective of the CAST program was to overcome some of the barriers to transitioning autonomous capabilities out of the lab. First, the system would need to be relatively low cost, a fraction of the target platform cost. CAST could not satisfy the cost objective required, given the system design and architecture (*13*).

U.S. Army AMAS (2012–2014 / $11 million)

Similar to CAST, Lockheed Martin was awarded a contract to expand on its effort to Autonomous Mobility Applique System (AMAS) for a retrofit platooning kit that could be used for variety of platforms (tactical vehicles) at a cost lower than $35,000. Both AMAS and CAST are developed for off-road environments and currently are not capable of following the rules of the road (*14*).

Auburn University Platooning (2013–2016 / $1.2 million)

Funded by the Federal Highway Administration (FHWA), this Auburn University project investigated partial automation, including throttle and braking systems, for two-truck platooning by integrating V2V communications and adaptive cruise control (ACC) in order to achieve longitudinal control (*15*).

Japan Energy ITS (2008–2013 / $60 million)

The most ambitious fully automated driving activity appears to be occurring in Japan's Energy ITS project, which has been developing and testing a platoon of three fully automated trucks for close to 5 years. This project, under the sponsorship of Ministry of Economy, Trade and Industry through its New Energy Technology Development Organization, has been funded at the equivalent of about $12 million per year for 5 years. The primary goal is to attain energy savings (CO_2 reductions) through the reduction of aerodynamic drag by operating trucks in an electronically coupled platoon at shorter-than-normal gaps, with additional objectives of improving highway traffic flow and safety. This study tries to address some technological issues related to passive safety within a truck platooning system. When the gap of the platooning trucks is reduced, a passive safety device is necessary. Preliminary development of a shock absorber is being tested to be placed on the front and back of the platooning truck. Applications of shock absorbers would also address safety issues in case of frontal/rear crash involving the trucks with smaller vehicles that could possibly position themselves between platooning trucks (*16*).

SCOPE AND PURPOSE

The TTI team investigated and documented lessons learned from past platooning projects; identified potential regulatory or legislative roadblocks that could hamper or facilitate introduction of platooning into commercial fleet operations; and explored the possible business cases and implementation scenarios within the existing infrastructure and operational environment. The TTI team also developed, tested, and demonstrated the platooning technology (proof-of-concept), which culminated in a full-scale demonstration workshop in July 2016 in College Station, Texas, to disseminate the results; capture insights, comments, and buy-in from stakeholders; and set the stage for further development and deployment on Texas roadways.

DOCUMENT OVERVIEW

This report is divided into the following eight chapters and four appendices and provides a comprehensive summary of the research undertaken as part of this project. The titles of each chapter and the major topics covered are highlighted below:

- **Chapter 1: Project Overview.** Provides an overview of the research project, including background, scope, and purpose.
- **Chapter 2: Setting the Stage.** Conveys the results of a review of state and federal code to identify regulatory and legislative hurdles that may delay or deter platooning operations in Texas. It includes regulations reviewed at both the federal and state level, focusing mainly on Texas measures.
- **Chapter 3: Development of Platooning Strategies.** Summarizes the effort to identify truck platooning scenarios that can be technically, economically, and legally implemented on Texas highways.
- **Chapter 4: Platooning Scenario Validation.** Describes the efforts undertaken to validate the platooning scenarios identified by the research team.
- **Chapter 5: System Development for Truck Platooning Demonstration.** Documents the preliminary analysis of requirements and specifications for the platooning system that were used for the formal system development.

- **Chapter 6: Fuel Savings and Emissions Measurement.** Summarizes the results of the fuel savings and emissions measurements for the platooning demonstration.
- **Chapter 7: Truck Platooning Demonstration Preparation.** Documents the process undertaken by the research team to prepare the commercial trucks and trailer for the platooning demonstration.
- **Chapter 8: Truck Platooning Phase 1 Demonstration.** Provides a summary of the platooning demonstration effort along with the scenarios exhibited during the proof-of-concept demonstration.
- **References.** Gives a detailed list of the references with citations documented throughout the report.
- **Appendix A: FMVSS Exemption Regulatory Process.**
- **Appendix B: Task 2 Stakeholder Interview Questions.**
- **Appendix C: Task 3 Stakeholder Interview Questions.**
- **Appendix D: TTI Platooning Vehicle and Subsystem Technical Specifications.**

CHAPTER 2: SETTING THE STAGE

INTRODUCTION

Commercial truck platooning is a relatively novel concept in Texas and around the country. Platooning enables commercial trucks to travel closely together while at high speeds without the worry of collisions, which can provide environmental benefits and reduce fuel and operational costs. Vehicle communications and carefully controlled automation technologies enable the system, and while the technologies are mostly mature, legal, administrative, and regulatory issues may yet prove barriers to deployment.

The research team reviewed regulations at both the federal and state level, although the in-depth review of state-level searches focused mainly on Texas measures, to identify regulatory and legislative hurdles that may delay or deter platooning operations in Texas. It also provides the results of stakeholder interviews focused on identifying liability issues and potential strategies to address those issues.

The federal review covers regulations, recommendations, and standards from:

- FMCSA.
- Federal Motor Vehicle Safety Standards (FMVSS).
- National Highway Traffic Safety Administration (NHTSA).
- FHWA's CV program.

The federal review uncovered potentially relevant regulations at FMCSA, standards from FMVSS, and informal guidance and early regulatory movements from both NHTSA and FHWA on CV/AVs. The research team analyzed these areas to determine any potential applicability or conflict with the proposed platooning system. Since the platooning concept is not fully developed, the research team highlighted potentially relevant regulatory and legislative areas, which enable additional evaluation as the project progresses.

The state-level review initially covered the legislation and regulations that other states have passed in recent years that specifically focus on AVs. Researchers then considered the relevant Texas laws and regulations that could affect platooning. The research team reviewed relevant sections from the Texas Transportation Code (TTC), regulations promulgated by state agencies, and recent legislative proposals.

POTENTIALLY RELEVANT FEDERAL REGULATIONS

The research team reviewed federal regulations related to CV/AVs and specific to trucks and commercial motor carriers, and sought to identify any areas that could potentially affect the proposed truck testing. Because the truck platooning concept is not yet finalized, the research team used a broad interpretation when determining potential relevance. Essentially, if it seemed a regulation or part of governmental code could plausibly affect commercial truck platooning, it was included. This provided a wide array of findings, although most are unlikely to directly affect the platooning concept. The platooning trucks will likely be equipped with production-intent equipment, which will result in minimal concerns.

As a note, this project focused on deployment, but testing is a necessary step to reach that goal. As such, this review covers regulations and legislation that also relate to testing. The terms "deployment" and "testing" are used throughout to express this necessary focus.

Truck-Specific Regulations

The research team found federal regulations relevant to CV/AV truck testing in two main areas:

- FMCSA, which regulates commercial vehicles.
- FMVSS, which sets vehicle safety standards.

Given the understanding that the eventual pilot platooning project may change and new concerns may arise, this review addressed a wide range of regulations that could affect the eventual testing program. This section highlights potentially applicable regulations with the understanding that these and other regulations may require further evaluation as the project progresses. The research team assumed changes could be made to any part of the truck responsible for controlling the vehicle (e.g., throttle, steering, braking, transmission) and sought to identify any regulations that deal with these areas. This provides a broad scan of potential changes that could occur and ensures that most relevant regulations will be considered.

Federal Motor Carrier Safety Administration

The research team reviewed the FMCSA regulations, under 49 CFR Parts 300-399, and identified a variety of potentially pertinent areas (*17*). Many of the potentially relevant regulations originated from three main sections:

- Part 392: Driving Commercial Vehicles (*18*).
- Part 393: Parts and Accessories Necessary for Safe Operation (*19*).
- Part 395: Hours of Service for Drivers (*20*).

Table 2 shows the specific sections, a brief summary of the regulation, and the potential relevance to a proposed CV/AV truck system. Before implementing any truck testing program, it may be helpful to review the details of these regulations. Knowledge of the specific implementation parameters will enable a more refined analysis and ensure there are no regulatory hurdles.

Table 2. Potential Relevant Sections of the FMCSA Regulations.

Title	Text or Summary	Potential Relevance
Part 381.4: Waivers, Exemptions, and Pilot Programs (*21*)	Details the requirements relating to getting temporary relief from regulations.	A pilot program can be granted temporary relief from regulations for up to three years.
Part 392.82 Using a Handheld Mobile Telephone (*22*)	Drivers cannot use a handheld mobile telephone while driving a commercial motor vehicle (CMV).	Any modifications cannot require that a driver use a handheld mobile telephone.
393.3: Additional Equipment Requirements (*23*)	Additional equipment that decreases safety is prohibited, but other equipment—as long as it does not reduce safety—is not prohibited.	Any modifications cannot decrease safety; other equipment is not necessarily banned.
393.9: Lamps (*24*)	Lamps must be operated at all times and cannot be obscured by other equipment or material.	Any modifications cannot obscure lamps, or render them inoperable.
393.19: Hazard Warning Signals (*25*)	"The hazard warning signal operating unit on each commercial motor vehicle shall operate independently of the ignition or equivalent switch, and when activated, cause all turn signals required by § 393.11 to flash simultaneously."	Any modifications must leave the hazard warning signals capable of operation independent of the ignition switch.
393.28: Wiring Systems (*26*)	"Electrical wiring shall be installed and maintained to conform to SAE J1292."	Any modifications to the wiring systems must conform to these standards.
393.30: Battery Installation (*27*)	This section provides detailed instructions on battery installation.	Any modifications that involve the battery must not violate these requirements.
393.40: Required Brake Systems (*28*)	This section provides, in specific detail, the exact ways brakes of differing varieties must operate.	Any modifications that involve the brakes must not violate these requirements.
393.51: Warning Signals (*29*)	Commercial motor vehicles must be equipped with warning signals that inform the driver when a brake system fails, and must meet certain requirements.	Any modifications that involve the brakes must not violate these requirements.
393.52: Brake Performance (*30*)	Describes the manner in which braking systems must perform.	Any modifications that involve the brakes must not violate these requirements.
393.80: Rear-Vision Mirrors (*31*)	Describes the requirements on where mirrors can be placed, the number of mirrors required, and other related information.	Any modifications that involve rear-vision mirrors must not violate these requirements.
393.201: Frames (*32*)	Describes the requirements for frames; parts and accessories cannot be welded to the frame or chassis.	Any modifications cannot be welded to the vehicle's frame.
393.209: Steering Wheel Systems (*33*)	Describes the requirements and standards for steering wheels and associated components.	Any modifications that involve the steering system must not violate these requirements.
395.1: Hours of Service of Drivers (*34*)	This section places limitations on the maximum hours of service for drivers.	Modifications may need to consider how hours of service will change with automated systems.
395.15: Automatic On-Board Recording Devices (*35*)	Authorizes and establishes requirements for on-board devices that record a driver's hours of service.	Modifications may need to consider how hours of service recording devices will change with automated systems.
Part 396.3: Inspection, Repair and Maintenance (*36*)	Establishes requirements for inspecting, repairing, and maintaining commercial vehicles. The requirements include any "parts and accessories which may affect safety of operation."	Any modifications may be held to these requirements. Additional and more frequent inspection may be required for platooning.

Federal Motor Vehicle Safety Standards

Researchers reviewed the FMVSS to identify any pertinent standards that could affect the CV/AV truck platooning testing program (*37*). The research team determined that many standards could be relevant, depending on how the eventual system is implemented. Standards cover areas such as brakes and braking systems; mirrors, lamps, and reflective devices; and accelerator control systems.

Each standard defines the requirements for a particular vehicle feature and the implications on the truck testing program are essentially the same under each: the potential truck testing program cannot violate these standards, unless it first gets a waiver under Part 555. This part provides for temporary relief from motor vehicle safety standards for a few reasons, but most relevant to the purposes of this study is the exemption for "the development of new motor vehicle safety… features" (*38*). Once the final design for the testing program is determined, the research team may wish to revisit these safety standards and assess the need to apply for an exemption. Table 3 provides standards identified that could potentially trigger the need for an exemption. Since the vehicle market currently produces and sells vehicles with ACC, which is functionally similar to the system required for platooning, the regulatory concerns to implement a similar system on commercial vehicles may be minimal.

Table 3. Potential Relevant Sections of the FMVSS.

Section and Title	Summary	Potential Relevance to Platooning
Standard No. 101: Controls and Displays (*39*)	This standard requires that essential controls be located within reach of the driver when the driver is restrained by a lap belt and upper torso restraint, and that certain controls mounted on the instrument panel be identified.	Modifications to vehicles must keep essential controls within the driver's reach, and any new controls must be identified.
Standard No. 102: Transmission Shift Lever Sequence, Starter Interlock, and Transmission Braking Effect (*40*)	This standard specifies the requirements for the transmission shift lever sequence, a starter interlock, and for a braking effect of automatic transmissions, to reduce the likelihood of shifting errors, starter engagement with vehicle in drive position, and to provide supplemental braking at speeds below 40 km/h (25 mph).	Current production ACC systems use automatic transmission shifts for deceleration (e.g., engine/transmission braking effect) under specific conditions. It is possible that the platooning system control strategy will differ somewhat in in the usage of transmission braking. Any eventual modifications to transmission or the named components cannot remove or invalidate these required components and system performance.
Standard No. 105: Hydraulic and Electric Brake Systems (*41*)	This standard specifies requirements for vehicles equipped with hydraulic and electric service brake systems and associated parking brake systems to ensure safe braking performance under normal conditions and emergency conditions.	Any modification to hydraulics or electrical braking systems cannot remove or invalidate these required components nor result in unsafe braking performance during normal or emergency braking conditions.
Standard No. 106: Brake Hoses (*42*)	This standard establishes performance and labeling requirements for hydraulic, air, and vacuum brake hoses, brake hose assemblies, and brake hose fittings for all motor vehicles. The purpose of this standard is to reduce brake system failure from pressure or vacuum loss due to hose or hose assembly rupture.	Any modification to brake hoses and related systems cannot remove or invalidate these required components.
Standard No. 108: Lamps, Reflective Devices, and Associated Equipment (*43*)	This standard specifies requirements for original and replacement lamps, reflective devices, and associated equipment. Its purpose is to reduce traffic crashes and deaths and injuries resulting from traffic crashes, by providing adequate illumination of the roadway, and by enhancing the conspicuity of motor vehicles on the public roads so that their presence is perceived and their signals understood, both in daylight and in darkness or other conditions of reduced visibility.	Any modification to lamps, reflective devices, and associated equipment cannot remove or invalidate these required components. Current production ACC systems apply the brake lamps when the system brakes. The platooning systems will need to consider this and turn signal application during lane changes. Other elements of FMVSS 108 may also apply.
Standard No. 111: Rearview Mirrors (*44*)	This standard specifies requirements for the performance and location of inside and outside rearview mirrors. Its purpose is to reduce the number of deaths and injuries that occur when the driver of a motor vehicle does not have a clear and reasonably unobstructed view to the rear.	Any modification to the vehicle for platooning cannot remove or invalidate these requirements for rearview mirrors.
Standard No. 121: Air Brake Systems (*45*)	This standard specifies performance, equipment, and dynamometer test requirements for braking systems on vehicles equipped with air brake systems, including air-over-hydraulic brake systems, to ensure safe braking performance under normal and emergency conditions.	Any modification to air brakes and related systems cannot remove or invalidate these required components or result in unsafe brake system operations under the stated conditions.

Section and Title	Summary	Potential Relevance to Platooning
Standard No. 124: Accelerator Control Systems (*46*)	This standard establishes requirements for the return of a vehicle's throttle to the idle position when the driver removes his or her foot from the accelerator control, or in the event of a severance or disconnection in the accelerator control system.	Any modification to accelerator control systems cannot remove or invalidate these system requirements; however, we note that current production cruise control and ACC systems continue to apply throttle control with the driver's foot off of the accelerator.
Part 555: Temporary Exemptions from Motor Vehicle Safety Standards (*38*)	This regulation provides a means by which manufacturers of motor vehicles may obtain temporary exemptions from specific safety standards on the grounds of substantial economic hardship, facilitation of the development of new motor vehicle safety or low-emission engine features, or existence of an equivalent overall level of motor vehicle safety.	This section lays out the availability and requirements for acquiring an exemption from FMVSS requirements.

Exemptions from the FMVSS are governed under Part 555, which are given in the cases of "substantial economic hardship to a manufacturer, the facilitation of the development of new motor vehicle safety or low-emissions engine features, or the existence of an equivalent overall level of motor vehicle safety" (*38*). Appendix A includes details on relevant parts of the application process, including the application process itself, the basis for applications, and how NHTSA processes applications.

Exemptions are given to a "manufacturer of motor vehicles or passenger motor vehicles" under three conditions:

1. On the bases of substantial economic hardship;
2. Making easier the development or field evaluation of new motor vehicle safety or impact protection or low-emission vehicle features; or
3. Compliance with a standard would prevent it from selling a vehicle with an overall level of safety or impact protection at least equal to that of non-exempted vehicles.

It is unclear if the current project would qualify for exemptions, as neither TTI nor TxDOT is a manufacturer of motor vehicles. However, the uniqueness of the current project may qualify the team under the second condition. Platooning can potentially reduce emissions and might improve safety, which could potentially qualify the project for exemption.

NHTSA RECOMMENDATIONS ON AUTOMATED VEHICLES

Currently, there are no federal regulations on AVs. Like the application of most technologies, the federal government has thus far taken a cautious and limited approach to regulating AVs, choosing to let states take the lead in regulating the AV industry rather than taking a direct role. In 2013, NHTSA released a document entitled "Preliminary Statement of Policy Concerning Automated Vehicles" addressing the burgeoning AV technology (*47*); the document laid out the agency's research agenda, a taxonomy for AVs (see Table 4), and proposed guidelines for states wishing to regulate AVs. Importantly, rather than proposing regulations on AVs, the agency chose to develop guidelines that states could voluntarily follow when regulating the AVs.

Table 4. NHTSA Automation Levels (from *48*).

NHTSA Automation Level	Description
Zero: None	The driver is "in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls" (p. 4). The vehicle may have the ability to monitor the environment but only for driver support, information, or convenience systems.
One: Function-Specific	The vehicle has "one or more specific control functions are automated," but the driver still has "overall control" of the vehicle and is responsible for its safe operation (p. 4). If multiple control systems are engaged, they operate independently. The vehicle may "assist or augment the driver in operating of one of the primary controls—either steering or braking/throttle controls (but not both)."
Two: Combined-Function	Two or more of the "primary control functions" work in automated unison to monitor the road and control the vehicle (p. 5). The driver maintains primary responsibility for safe operation road monitoring and must be available to take over control at any time without advance warning.
Three: Limited Self-Driving	The vehicle controls all "safety-critical functions under certain traffic or environmental conditions" (p. 5). The driver need not constantly monitor the roadway and can rely on the vehicle to do so. If the situation changes and the vehicle cannot operate safely, it provides sufficient advanced warning to the driver—who must be available—to take control.
Four: Full Self-Driving	The "vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip" (p. 5). The driver may need to provide directions for navigation but does not need to control the vehicle at any point. The vehicle could be unoccupied or occupied, and is solely responsible for safe operation.

NHTSA begins the recommendations by establishing the boundaries under which regulations should occur (see Table 5). The agency expresses its concern that premature or misguided regulations could harm the nascent AV industry, stating that all regulations must "appropriately balance the need to ensure motor vehicle safety with the flexibility to innovate" (p. 10). To avoid such harm, the agency encourages states to take a cautious approach when regulating. For example, the agency encourages states to only regulate NHTSA level 3 and 4 vehicles for testing purposes, and not authorize automation for any other purposes.

The agency recommends that states avoid developing specific safety standards or regulating the safety of self-driving vehicles for purposes beyond testing. This poses somewhat of a conflict and difficulty for states, as states traditionally regulate drivers, and the federal government traditionally regulates vehicle safety. AVs could upset this balance; an AV that is responsible for the driving task becomes the driver and blurs the line between regulating driver and vehicle.

Table 5. NHTSA Recommended Regulatory Boundaries.

Regulations should	Regulations should not
• Focus on NHTSA level 3 and 4 vehicles only. • Focus on "licensing, driver training, and conditions for operations related to specific types of vehicles." • Ensure that only original equipment manufacturers employees or designees can operate test vehicles, and only for testing purposes.	• Permit "operation of self-driving vehicles for purposes other than testing." • Develop detailed regulations on the safety of self-driving vehicles for purposes other than testing. • Regulate the technical performance of AVs.

Following the initial recommendations, the agency includes four broad recommendations, each with associated subrecommendations. The first focuses on ensuring the driver of the AV is adequately trained and knows how to operate the vehicle. The second recommends states focus their regulations on the circumstances under which testing will occur—ensuring that testing minimizes risks to other road users, is monitored for any problems, and occurs under road conditions the AV can handle. The third recommendation lays out principles guiding AV testing, like ensuring "the process for transitioning from self-driving mode to drive control is safe, simple, and timely." The final recommendation the organization offers is that states should not develop regulations for purposes other than testing, but if they do, they recommend that (at a minimum) (*39*):

> The state should require that a properly licensed driver (i.e., one licensed to drive self-driving vehicles) be seated in the driver's seat and be available at all times in order to operate the vehicle in situations in which the automated technology is not able to safely control the vehicle.

These recommendations are likely to have limited or no direct influence on the proposed platooning program for a few reasons. First, these are recommendations and not regulations; because NHTSA has chosen to not yet pass regulations, states are free to establish rules for automation as they deem appropriate. Additionally, platooning is likely a level 2 automated system, which NHTSA does not recommend states regulate.[1] None of the states to enact laws on automation have addressed level 2 systems, and most specifically avoid regulating these and other advanced driver assistance systems. Finally, Texas has not yet chosen to adopt any regulations on AV testing or operation. As shown in the following sections, some preexisting laws governing vehicles may make platooning challenging, but none relate to automation, per se.

FEDERAL REGULATIONS ON CONNECTED VEHICLES

Platooning requires some form of vehicle communications to prevent platoons from breaking down or colliding when traveling at high speeds (*48*). Instantly communicating a change in status, like braking, allows following vehicles (FVs) to also respond instantly, keeping all vehicles moving in unison. One of the most likely candidates for such communication is DSRC radios, using V2V communications. The U.S. Department of Transportation (USDOT) selected this technology and developed associated standards and protocols for use in vehicles to relay safety-critical information with very low latency and high availability. Other communications systems (like Wi-Fi or cellular) can have higher latency, which slows information transmission, and lower availability, which results in messages not being reliably conveyed in a timely manner.

[1] Combined Function Automation, or NHTSA Level 2 Automated Vehicles have "at least two primary control functions designed to work in unison to relieve the driver of control of those functions" (*47*). A driver in a Level 2 vehicle can safely have "his or her hands off the steering wheel AND foot off the pedal at the same time," although the automated system "can relinquish control with no advance warning and the driver must be ready to control the vehicle safely."

These disadvantages disqualify these communications systems for safety-critical information transmission. These same criteria make DSRC a likely candidate for platooning systems. The use of DSRC at the dedicated 5.9 GHz spectrum ensures messages are sent quickly and reliably. As such, it is worth reviewing regulations and guidance promulgated by the federal government on the CV system to ensure the research team is abreast of any potential regulatory hurdles.

Since many aspects of the CV system are not yet ready for deployment, FHWA, NHTSA, and other federal agencies have not released final regulations for the system. The first formal regulations for CVs are under development at NHTSA, which would mandate the deployment of CV systems on all new light vehicles. In August 2014, the agency released the Advanced Notice of Proposed Rulemaking, which publically proclaimed NHTSA's intent to eventually create regulations (propose rulemaking) for the CV system (*49*). The proposed rule would create a new FMVSS, No. 150, which would "require vehicle-to-vehicle communication capability for light vehicles (passenger cars and light truck vehicles) and to create minimum performance requirements for V2V devices and messages" (*50*). NHTSA is also assessing whether to mandate the system on commercial vehicles, and stated during the 2015 ITS America Annual Meeting that the agency would, "have an announcement [on moving forward with the regulatory steps needed for a mandate] as soon as this year [2015]" (*51*). Additionally, a NHTSA report on the agency's priorities for vehicle safety and fuel economy states that it expects to "complete research necessary to support an agency decision on heavy vehicle V2V" and issue a decision in 2015 (*52*).

NHTSA occasionally receives questions on its rules from the public. When this happens, its Chief Council will interpret the agency's rules and respond with a letter of interpretation. These letters are considered the opinion of the agency at that *time*, and as such are not binding and do not set precedent. Nonetheless, the agency states these interpretations "may be helpful in determining how the agency might answer a question that you have if that question is similar to a previously considered question" (*53*). This resource may be worth reviewing when or if questions about NHTSA regulations arise.

POTENTIALLY RELEVANT STATE LEGISLATION AND REGULATIONS

The research team reviewed state legislation and regulations that were specific to AVs and commercial trucks. Since Texas has not passed a law related to AVs, researchers looked at enacted legislation and regulation in other states. The review of commercial vehicle legislation and regulation, however, focused entirely on Texas since it is the focus of the study.

AV-Specific Legislation and Regulations

To date, six states (California, Florida, Michigan, Nevada, North Dakota, and Tennessee) and Washington, D.C., have passed laws authorizing AVs for operation and/or testing (see Table 6). These laws specifically do not regulate low-level automation—such as collision prevention, lane keeping, or automatic parking—but instead focus on high-level automation, such as NHTSA level 3 or 4 vehicles (see Table 4 above for definitions).

Table 6. Enacted AV Laws.

State	Law	Passage Date
California	SB 1298 (54)	9/25/2012
District of Columbia	B19-0931 (55)	1/23/2013
Florida	CS 1207 (56)	4/16/2012
Florida	SB 52 (57)	5/29/2013
Michigan	SB 169 (58)	12/26/2013
Michigan	SB 663 (59)	12/27/2013
Nevada	AB 511 (60)	6/17/2011
Nevada	SB 140 (61)	6/17/2011
Nevada	SB 313 (62)	6/2/2013
North Dakota	HB 1065 (63)	3/20/2015
Tennessee	HB 0616 (64)	5/6/2015

The laws governing AVs vary considerably across the states; they authorize AVs for public use, for testing by private companies only, or allow some combination of both public use and private testing (see Table 7). Several states passed an initial law establishing the legal framework for AV testing, but then also directed their departments of motor vehicles (DMVs) to develop a program overseeing testing and/or public operation.

Only authorizing AVs for testing allows original equipment manufacturers or other approved entities (such as component manufacturers or software developers) to test their vehicles on state roads, or other areas, as authorized by the state. The impetus for this sort of authorization originates with the perception that AVs are not yet fully developed or safe, and regulating vehicle testing would enable a state to oversee the activities taking place on its roads. Such oversight would hypothetically make the roads safer by requiring testers to abide by certain rules, report infractions or crashes, operate in certain conditions, or other restrictions. California, for example, requires AVs record and report data to the state relating to any crashes that might occur on test vehicles.

Table 7. Legislative Overview.

Policy Aspect	CA	FL	MI	NV	D.C.	ND	TN
Permits Testing	X	X	X	X	X	X	
DMV to Develop Regulations	X	X		X	X		
Permits Public Operation	X	X			X	X	
Silent on Public Operation				X			X
Bans Public Operation			X				

While most of the states explicitly authorize AVs for testing purpose, they take very different approaches to public use. Several states either explicitly authorize or ban public operation, while others are less clear about public operation. Tennessee, for example, only prohibits political subdivisions (like counties or cities) from “prohibit[ing] the use of a motor vehicle within the jurisdictional boundaries of the political subdivision solely on the basis of being equipped with autonomous technology” (*64*). The state chose not to explicitly authorize the vehicles, but instead banned local governments from prohibiting their use. Nevada took a similar approach, by remaining silent as to whether or not they authorize public use.

This ambiguity is likely intentional, as a state that does not specifically ban AVs is essentially rendering them legal to operate by the general public. As Smith explains in his paper *Automated Vehicles are Probably Legal in the United States*, a longstanding and fundamental legal principle holds that “everything is permitted that is not prohibited” (*65*). In other words, everything is legal, unless there is a law that prohibits it. Smith argues that this basic legal principle renders AVs legal, unless they are specifically made illegal. It follows that the states’ silence on whether or not the public can operate AVs renders them legal to operate publically. Only one state specifically banned automation, Michigan, which restricts operation to “automation manufacturers” when testing their vehicles (*51*, *66*).

Because Texas has not yet passed any laws or regulations related to AVs, the vehicles are legal to operate in the state. Any eventual testing program using automation does not need to consider state laws or regulations specifically related to automated driving.

Truck-Specific State Regulations

Researchers reviewed the Texas statutes with the purpose of identifying existing laws that could affect the CV/AV truck platooning pilot. The research team found state regulations with potential relevance in two areas:

1. TTC, which regulates transportation activities.
2. The Texas Administrative Code (TAC), which sets administrative standards for state agencies.

Given the understanding that the eventual pilot platooning project may change and new concerns may arise, this review addressed a wide range of regulations that could affect the eventual testing program. This section highlights potentially applicable regulations with the understanding that these and other regulations may require further evaluation as the project progress. The research team assumed changes could be made to any part of the truck responsible for controlling the vehicle (e.g., throttle, steering, braking, transmission) and sought to identify any regulations that deal with these areas. This provides a broad scan of potential changes that could occur and ensures that most relevant regulations would be considered. Existing state regulations related to the truck platoon testing are summarized in the following section.

Texas Transportation Code

The research team reviewed the TTC regulations and identified many potentially pertinent areas. The highest concentration of potentially relevant regulations originated from two main sections:

- Title 6 – Roadways (*67*).
- Title 7 – Vehicles and Traffic (*68*).

Table 8 includes the specific sections, a brief summary of the regulation, and the potential relevance to a proposed CV/AV truck platooning system. Before implementing any truck testing program, it may be helpful to review the details of these regulations. Knowledge of the specific implementation parameters will enable a more refined analysis and ensure there are no regulatory hurdles.

Table 8. Potential Relevant Sections of the TTC.

Section	Regulation Title	Summary	Potential Relevance to Platooning
224.1541 (69)	Exclusive Lanes	Exclusive lanes can be designated for the use of a particular class of vehicles to enhance safety, mobility, or air quality.	A platooning project that includes dedicated lanes may be applicable under this regulation.
541.001 (70)	Persons	This section defines terms for this subtitle including "operator" and "person."	Depending on interpretation, entities involved in platooning could be considered as operator or person involved and subject to the regulation.
542.302 (71)	Offense By Person Owning or Controlling Vehicle	A person who owns a vehicle or employs or otherwise directs the operator of a vehicle commits an offense if the person requires or knowingly permits the operator of the vehicle to operate the vehicle in a manner that violates law.	Depending on interpretation, an entity involved in platooning could be considered an owner and subject to the regulation.
545.002 (72)	Operator	"In this chapter, a reference to an operator includes a reference to the vehicle operated by the operator if the reference imposes a duty or provides a limitation on the movement or other operation of that vehicle."	Vehicles have the same responsibilities and duties as human vehicle operators, so CV/AV trucks must adhere to the same rules of the road as all other drivers.
545.062 (73)	Following Distance	"An operator shall, if following another vehicle, maintain an assured clear distance between the two vehicles so that, considering the speed of the vehicles, traffic, and the conditions of the highway, the operator can safely stop…"	The first section requires vehicles to leave enough room between vehicles to ensure the operator can safely stop, which could potentially be construed as a legal hurdle to platooning.
		"An operator on a roadway outside a business or residential district driving in a caravan of other vehicles or a motorcade shall allow sufficient space between the operator and the vehicle preceding the operator so that another vehicle can safely enter and occupy the space. This subsection does not apply to a funeral procession."	This requires that vehicles traveling in caravans outside a business or residential district leave sufficient space between vehicles to allow another vehicle to merge between the vehicles. The legislative code seems to ban platooning in this specific situation.
545.417 (74)	Obstruction of Operator's View or Driving Mechanism	This section disallows any load or additional passengers from obstructing the operator's views.	Any modifications that could obstruct the operators view must consider these requirements.
545.425 (75)	Use of Wireless Communication Device in a School Crossing Zone	This section restricts the use of commercial wireless communication devices[2] in a school zone.	Any testing that involves wireless communication devices must not violate these restrictions while in a school zone.
547.401 (76)	Brakes Required	A motor vehicle, trailer, semitrailer, pole trailer, or combination of those vehicles shall be equipped with brakes.	Any modifications that involve the brakes must not violate these requirements.
547.402 (77)	Operation and Maintenance of Brakes	This section provides, in specific detail, the exact ways brakes of differing varieties must operate.	Any modifications that involve the brakes must not violate these requirements.

[2] In this section, a wireless communication device is defined according to 47 U.S.C. Section 332, which defines commercial mobile service as "any mobile service that is provided for profit and makes interconnected service available to the public or to such classes of eligible users as to be effectively available to a substantial portion of the public, as specified by regulation by the Commission."

Section	Regulation Title	Summary	Potential Relevance to Platooning
547.615 (78)	Recording Devices	Regulates the use of recording devices[3] in a vehicle and the use of the collected data.	Any modifications that include information recording devices may need to consider these requirements.
621.101 (79)	Maximum Weight of Vehicle or Combination	This section includes restrictions and requirements for motor vehicles and truck-tractors.	Any modifications may be held to these requirements.
621.205 (80)	Maximum Length of Vehicle Combinations	This section includes restricts coupling trucks and tractors to a maximum combined length of 65 feet.	This section seems targeted to trucks that are physically coupled, but may be worth considering further.
646.001 (81)	Motor Transportation Brokers	This section defines motor transportation broker as a person who “sells, offers for sale, provides, or negotiates for the transportation of cargo by a motor carrier operated by another person.”	Depending on interpretation and implementation, an entity involved in platooning could be considered a broker and subject to the regulation.

[3] State code defines a recording device as “a feature that is installed by the manufacturer in a motor vehicle and that does any of the following for the purpose of retrieving information from the vehicle after an accident in which the vehicle has been involved: records the speed and direction the vehicle is traveling; records vehicle location data; records steering performance; records brake performance, including information on whether brakes were applied before an accident; records the driver's safety belt status; or transmits information… to a central communications system when the accident occur.”

Perhaps the most relevant sections from the code are found in section 545, where the code requires vehicles traveling in caravans outside a business or residential district leave sufficient space between vehicles to allow another vehicle to merge between the vehicles. This specific situation is one where platooning would be restricted from occurring. Another noteworthy potential hurdle from the same section requires vehicles to leave enough room between vehicles to ensure the operator can safely stop, which could potentially be construed as a legal hurdle to platooning.

Texas Administrative Code

The TAC was reviewed for potentially relevant regulations. Title 43 of the TAC represents administrative regulations that relate to transportation and all related agencies. A review of this title did not find specific regulations with direct implications for truck platoon testing, but a couple of sections may be relevant for reference during the project. Part 1 outlines the regulations for implementing lane use restrictions for congestion relief and/or by class of vehicle, which is listed in Table 9.

Table 9. Potential Relevant Sections of the TAC.

Part 1 – TxDOT			
Chapter 25 Traffic Operations	Subchapter C (*82*)	Congestion Mitigation Facilities	This chapter presents regulations for HOV lanes, including how to limit the use of lanes to particular vehicles.
	Subchapter J (*83*)	Restrictions on Use of State Highways	This chapter presents the regulations guiding how a local jurisdiction or the department of transportation (DOT) can implement highway lane use restrictions, included by class of vehicle.

While these sections may not restrict platooning, some may be worth heeding due to their potential relevance to other aspects of platooning that might be considered. For example, the provision on congestion mitigation strategies allows for the limitation of lanes for particular vehicles, which could potentially serve as a test bed for platooning trucks. This section allows the Transportation Commissioner to designate an exclusive lane and finance its construction if it will "improve transportation safety, mobility, or air quality." Since platooning could improve at least two of these areas, it is possible that this designation could apply for platooning vehicles.

Recent Relevant Legislation

One proposed bill related to truck following distance was introduced to the Texas Legislature in 2013 and is currently "pending in committee" (*84*). The bill suggests the following addition to Chapter 642 of the Transportation Code:

> Sec. 642.004. TWO OR MORE COMMERCIAL MOTOR VEHICLES TRAVELING IN CONVOY - All trucks traveling in convoys of 2 or more with gross vehicle weight of 26000 pounds or more must maintain a minimum following distance of 150 feet between each vehicle when traveling on two lane state highways.

LIABILITY ISSUES AND CONCERNS

This section documents the investigation of potential truck platooning liability issues and the discussion of strategies to address liability issues. The research team reviewed relevant literature related to liability from commercial truck platooning and conducted a series of interviews with subject matter experts on the topic to gauge the current industry perspectives on the issue. The findings from both activities formed the basis for strategies to address the liability concerns. The following sections summarize the results of the assessment of potential truck platooning liability issues in Texas from the perspective of critical stakeholders and subject matter experts.

INTERVIEW METHODOLOGY AND PROCESS

As part of the effort to identify and document regulatory or legislative roadblocks that could hamper or facilitate introduction of platooning into the commercial fleet operation, the research team conducted a set of interviews with various stakeholders and subject matter experts. The objective of these interviews was to identify the operational challenges and risks associated with the project in order to consider countermeasures and mitigate the future risks related to truck platooning.

The research team contacted potential interviewees via email and conducted the interviews over the telephone. Interviewees were sent the questions in advance of the interview to help them prepare and ensure they were able to answer the questions. One researcher conducted the interview while another was available to take notes. The interviews were not recorded, and each lasted about 30 minutes. The stakeholders and experts identified for the interview process represented a range of perspectives. The areas of expertise include, but were not limited to:

- Trucking industry association representatives.
- Motor carrier safety experts.
- Legal experts.
- Insurance representatives.
- Public sector agency representatives (e.g., DOT, metropolitan planning organization).
- Toll road operators.

The researchers contacted 15 individuals during the initial recruitment. Ultimately, six interviews were conducted, representing a 40 percent response rate. This number fell short of the team’s internal goal of 10 interviews, but the final set of interviewees was considered satisfactory. The diversity and expertise of the sample ensured its overall robustness. The interview questions used in this task are provided in Appendix B.

These questions served as the structure for the interviews, although the applicability and usefulness of each question varied by respondent due to the diversity of the interview pool. Some questions also served as an opportunity to explain certain aspects of the project or platooning details (see question 2 for an example).

KEY CONCERNS

Based on the interviews and the literature reviewed previously, concerns surrounding liability and platooning originate from a few areas of uncertainty. The following section summarizes the results of the interview process in terms of three main areas of concern. The summary reflects a synthesis of the interviewees' perspectives on these issues and complementing the interview material with related findings from the literature. The three main areas discussed in this section are:

- Private liability concerns.
- Governmental liability considerations.
- Possible strategies to address liability.

Private Liability Concerns

Previous literature suggests that liability associated with any automated vehicular control systems will generally shift from the driver to the vehicle or technology manufacturer, but the magnitude of the shift will roughly correlate with the distribution of responsibility for the driving task (*85*). The concept of truck platooning requires that trailing drivers relinquish some degree of control of their vehicle to both the automated system(s) on their vehicle and to the driver in the lead vehicle (LV) of the platoon. Given those conditions, low-level, partially AVs will have different implications for the distribution of liability than high-level or fully AVs.[4]

Several of the subject matter experts echoed this viewpoint; they agreed that the liability will likely shift from the trailing driver that relinquishes control to manufacturers of the automated system and the lead driver controlling the vehicles.[5] One of the concerns, however, is that there is no certainty or guarantee that this transfer of liability will happen, so trucking companies may be reticent to engage in platooning without improved clarity in how liability will be apportioned.

One trucking industry respondent pointed out two related concerns: the variance in liability laws across states and perceived inequities in apportioning liability based on negligence. The individual cited Minnesota law as an example of these concerns, which holds that a commercial trucking company involved in a crash could be found only 20 percent negligent for the actions that caused the crash, but held 100 percent liable for harms that occur. The individual went on to

[4] Platooning systems are, depending on their configurations, either a level 2 or 3 (NHTSA) automated system.

[5] As with AVs, shifts in liability are likely to correspond with the degree of control that the driver cedes to the vehicle.

argue that the inconsistency in liability laws across states and this perceived inequitable treatment would discourage the company from engaging in platooning. Furthermore, the concerns on liability may even extend to using connected or other AV systems. The individual argued that tort reform was needed before truckers would adopt these technologies.

A legal expert interviewee countered this viewpoint, arguing that the law would not change to exempt truck drivers from liability if they were platooning; no matter the technology involved, motorists involved in crashes with commercial vehicles will still seek compensation from commercial vehicle drivers and operators. This individual went on to argue that the adoption of platooning technologies will be driven by market forces. In other words, if platooning is safer and saves trucking companies money, companies will adopt it. Those that do not adopt the capital-saving technologies will be at a competitive disadvantage to the early adopters, which would create pressure on others to also adopt the technology to level the economic playing field. Still, another respondent argued that it is not clear that increased fuel efficiency will be a sufficient incentive (especially given recent decreases in fuel costs) to take on new risks in light of the generally low-profit margins for commercial trucking and the potentially very high costs that could arise from increased liability.

Governmental Liability Considerations

Liability for government agencies from platooning activities is not likely to increase for a few reasons. First, interviewees and the literature agree that government agencies receive sovereign immunity or protection from prosecution because the state is sovereign. This protection is only waived in very specific circumstances, such as when government actors are negligent in a specific manner (*86*). An example might be if the government is informed that a part of the CV system is malfunctioning (like a roadside unit), but fails to repair the equipment in a timely manner. If harm occurs as a result of the malfunction, the government could be found negligent and lose its sovereign immunity protections as a result of the notice and failure to act.

A second reason governmental liability is unlikely to increase is the likelihood that the CV system, which platooning may or may not ultimately use, “does not create new or unbounded liability exposure for industry” (*5*). NHTSA argues that the CV system, (the development of which the federal government has funded, in which it has participated, and which state and local governments will likely implement) “from a products liability standpoint… analytically, are quite similar to on-board safety warning systems found in today’s motor vehicles.” The agency goes on to argue that it “does not view V2V warning technologies as creating new or unbounded liability exposure for industry” and as a result, does not have “a current need to develop or advocate the liability limiting agenda sought by industry in connection with potential deployment of V2V technologies” (*5*).

Possible Strategies to Address Liability

Perhaps the largest liability issue is the uncertainty that surrounds platooning and private companies. Based on existing law and analysis of similar cases, reasonable assumptions can be drawn about how liability for crashes will be handled. However, without either legal arrangements that directly outline liability or a real case that examines these issues at trial, this uncertainty will likely linger. One interviewee felt that federal regulations addressing this uncertainty would make the trucking industry “much more comfortable” with platooning. Another respondent pointed out that NHTSA’s eventual decision on mandating DSRC for commercial vehicles will allay some of the uncertainty but, critically, if it does not specifically address liability issues, the respondent felt the industry’s concerns will only grow.

Most interviewees said their organizations were not taking any steps to address liability concerns related to platooning, other than monitoring the issue for any developments. Some were aware of industry working groups that assess aspects of platooning but none that specifically focused on liability.

The research team asked respondents about a few hypothetical strategies to decrease this uncertainty and manage liability. Again, most respondents had not heard of industry attempts to address liability associated with platooning, but several proffered potential strategies seen in other industries. Several individuals pointed to ideas that involve insurance markets or policies. A legal expert explained that a lead driver could purchase an insurance policy that would insure against any liability associated with platooning. The lead driver would then charge individuals that join the platoon a fee to recoup insurance costs. This insurance coverage could even be an extension of an existing policy, where the truck would inform the insurance company about the platooning system, and the insurance company would price the premium based on the driver’s and system’s combined risk. The interviewee warned that the benefits from platooning would have to outweigh the insurance premiums for the system to be financially viable.

An insurance expert pointed to two different types of insurance groups that perform a similar function: insurance purchasing groups and risk-retention groups. The individual explained that a purchasing group is composed of members with similar risk exposures, who create a group to use their combined purchasing power to purchase insurance from a company. In a retention group, a group of similar members come together and create a pooled fund into which the members pay premiums, take losses, and collectively share risk. Both of these ideas stem from federal law, are legal, and currently exist in Texas (*87*, *88*). Trucking industry associations, for example, sometimes offer purchasing groups for their members.

Another legal expert pointed to the idea of risk shifting through contract-based risk management. Under such an arrangement, trucking companies and fleet operators (perhaps through an industry group) would develop a generalized agreement or contract wherein the members would agree to follow a set of rules governing inter-company platooning, including rules governing risk. The individual pointed out that risk shifting through contract-based risk management already occurs in other industries. In construction, for example, many subcontractors working on a single site will form an agreement covering site use and associated risks.

CONCLUSIONS

A high amount of uncertainty exists surrounding the liability impacts of truck platooning as revealed in both the interviewees and the literature. Furthermore, many unresolved questions remain that create uncertainty for the industry.

For the trucking industry, the uncertainty that surrounds platooning and related technology may leave companies hesitant to invest in these technological changes. Today, the trucking industry operates despite being faced with the costs and risks associated with current liability and existing tort law. The intervention of a government agency or other external actor could reduce the uncertainty or mitigate the risks.

While platooning technologies may shift the distribution of liability among owners and manufacturers, it was suggested that the current legal and insurance institutions are equipped to absorb these changes into its current structure. If the latter is true, market forces will drive the future of platooning.

Interviewees pointed to various forms of insurance that suggest ways to mitigate risks and lessen uncertainty. Another individual suggested contracts that establish rules governing platooning and risk sharing. Several other interviewees argued that government actions could help reduce uncertainty: the forthcoming NHTSA ruling mandating DSRC for commercial vehicles, developing federal regulations governing platooning and risk, and state tort reform. Other respondents felt tort reform would be unnecessary and unhelpful.

Finally, it is unlikely that platooning will not increase governmental agencies liability, as these agencies have sovereign immunity. This protection is only waived in a few special circumstances, like governmental negligence leading to harm.

CHAPTER 3: DEVELOPMENT OF PLATOONING SCENARIOS

INTRODUCTION

The research team performed a broad assessment of fundamentally different alternatives. At a high level, the research team accomplished the following in this effort:

- Identified alternative truck platooning concepts that may be technically, economically, and legally implemented on Texas highways in the next 5 to 10 years.
- Defined performance measures for evaluating different truck platooning system alternatives.
- Identified potential candidate locations where truck platooning may be beneficial.
- Began identifying organizational issues that need to be addressed prior to implementing truck platooning in Texas.

IDENTIFY ALTERNATIVE CONCEPTS

The following sections outline the process undertaken to identify the alternative concept for truck platooning.

Truck Platooning Operating Characteristics

For this project, platooning was permitted only between two commercial vehicles. Each commercial vehicle shall consist of a single truck tractor and a single semitrailer combination with the semi-tractor not to exceed 59 ft, the maximum semitrailer length allowed in Texas. The LV will be either manually driven or use ACC features to provide longitudinal control with driver input for lateral (steering) control. The driver of the FV will remain in the driver's seat, with the seat belt fastened, and will monitor the driving environment[6] (e.g., will not be completely disengaged from the driving task) for the entire time the trucks are operating in a platoon. The driver of the FV has primary responsibility and must be ready to take full control of the vehicle at any time without advance warning.

The FV will be equipped with automated longitudinal and lateral control after platooning is engaged. This FV will operate in automated ACC mode for longitudinal control with the driver controlling the steering (lateral motion) from the time a system is activated and a platoon formation request is sent until the system checks are acceptably completed and the platoon is formed (i.e., platooning is engaged). Once the platoon has engaged, the FV will then operate in (automated longitudinal) CACC mode and use automated (lateral) steering control. It will remain operating in this mode until the FV driver or LV driver disengages the platooning system. Once in a platoon, the FV will maintain longitudinal control at a fixed preset, driver-selectable gap or

[6] Note: the commercial truck platooning system is a level 2 automation systems per the NHTSA automation levels.

headway. It is expected that this gap will range from 20 ft (6 m) to 100 ft (30 m) with less than a 1 ft margin of error and will be selectable by the driver.[7]

Once in a platoon, the two vehicles should function as a single unit. This means that whenever a lane change is required, the LV must identify a gap that is large enough for both vehicles in the platoon to fit.[8] Truck platoons should primarily operate in the outside lane(s) depending on the total number of lanes present on the facility and should NOT travel for significant distances in the inside lane. The platoons may execute a lane change maneuver (as long as it is safe to do so) in order to overtake slower moving vehicles or to avoid vehicles entering the facility from a ramp; however, the driver shall disengage the platoon prior to leaving travel way.

The system shall be disengaged when the platoon encounters any one of the following operating situations:

- If the speed of the platoon of vehicles is not within the operating speed range (sustainable speed drops below 30 mph without stop-and-go system capability).
- If the driver overrides the system by:
    - Either driver manually disabling the system through a system switch.
    - The driver of the FV initiating a steering, brake, accelerator, or clutch input.
- If the platoon encounters unusual or unexpected driving conditions such as the following:
    - A maintenance or construction work zone.
    - Poor environmental conditions due to severe weather.
    - An emergency vehicle with its emergency warning lights activated.
    - A traffic incident.

Platooning may only be permitted in a predefined set of weather conditions, with the system setting being adjusted based upon deviation from these weather conditions to maintain safety. However, the systems should be robust enough to monitor the environment to provide safe and reliable operation in normal driving conditions. Operational guidance may also include recommendations for various states of pavement repair needs.

These select vehicles would not be permitted to participate in truck platooning:

- Vehicles carrying hazardous materials.
- Vehicles carrying fluids (e.g., tankers, concrete trucks).
- Vehicles carrying pipes, lumber, or similar types of loose loads.

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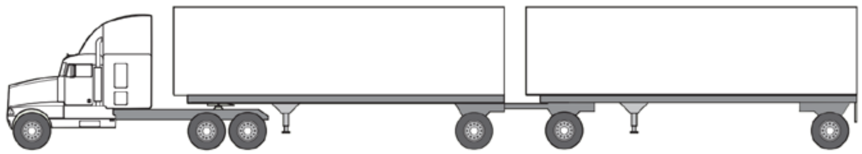
[7] The separation ranges and margin of error will be defined in Phase 2 of this project along all other system and operational requirements. All initial system and operational characteristics noted in this section are subject to change. Similarly, all other initial system and operational characteristics noted in this section are subject to change.

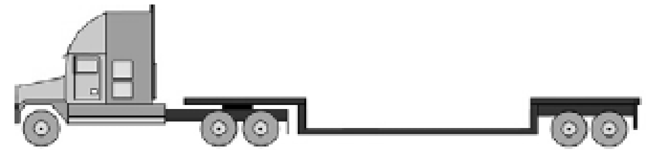
[8] This process may require input from the driver of the FV or communication of information from sensors on the FV to the LV.

- Automobile and boat transporter combinations (traditional and stinger-steered).
- Truck and pole combinations.
- B-Train combination.
- Lowboy tractor/trailer combinations (loaded and unloaded).
- Saddlemount or saddlemount with fullmount combinations.
- Construction vehicles (e.g., mobile cranes, concrete mixers).
- Recreational vehicles.

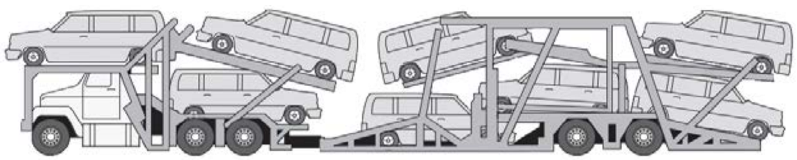
Figure 1 illustrates many of the vehicles not allowed to participate in the platooning in Texas. Trucks that are platooned will be identifiable by a decal or sign (similar in concept to that of a hazmat vehicle).



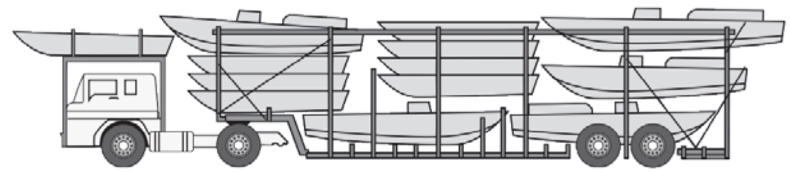
Double Trailer Combinations



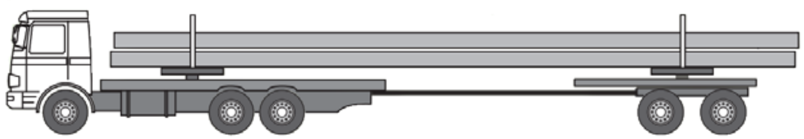
Truck with Lowboy Trailer



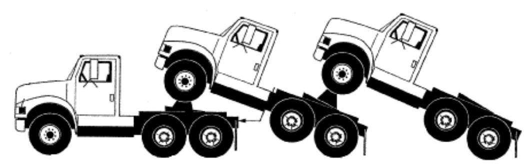
Commercial Truck and Stringer-Steered Semi-Trailer Combination Transporting Automobiles (or Boats)



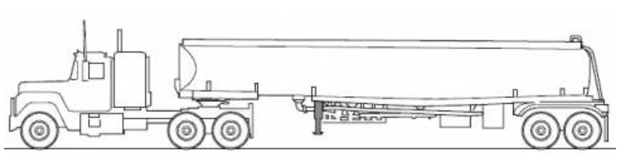
Traditional Boat or Automobile Transporter Combination



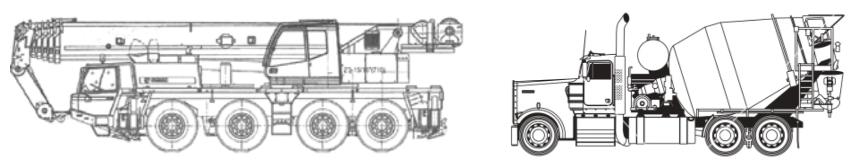
Truck and Pole Combination



Saddlemount Truck Combination



Tankers



Construction Vehicles

Figure 1. Example of Truck Trailer Configuration Not Permitted to Platoon.

Alternative Concepts for Truck Platooning

Using these operating characteristics, the TTI team identified a number of alternative concepts for implementing a truck platooning system in Texas. These alternative concepts are described below.

Ad Hoc On-the-Fly Platooning

This is the least restrictive of all the truck platooning concepts. In this alternative, any two commercial vehicles (assuming they are properly equipped to do so) can form an automated platoon. Under this alternative, the two vehicles would meet randomly on the road where no prior attempt has been made to coordinate platoon formation. Under this alternative, the FV would pull up behind the LV and the two commercial vehicles would automatically interrogate one another to determine if the vehicles are equipped with proper and compatible equipment that would allow the vehicles to form a platoon. If, through a series of system checks and information exchanges, the two vehicles determine that their systems are compatible, the system would notify the driver of the FV that platooning is possible. At that time, the driver of the FV should initiate a request to the driver of the LV to form a platoon through a driver interface. The driver of the LV would have the option to approve or deny the request. If the LV driver denies the request, then the driver of the FV should receive a message that the request is denied and the platoon formation procedure would cease or the LV has the option of conceding the lead position to the FV and then assume the follow position in the platoon. If the LV driver approves the request to form a platoon, then the driver of the FV should receive notification that platooning has been approved. Upon receipt of the approval from the LV, the two vehicles would initiate the coupling protocols. Once coupled (that is platooning engaged), the two vehicles would then operate as a single unit using CACC control. The driver of the LV would be responsible for guiding and controlling the platoon, while the driver of the FV would have the ability to override the system by either applying the brake or by applying force to the steering wheel. If CACC control is broken (platoon is disengaged), the two vehicles would be required to re-initiate the coupling protocols in order for the platoon to reform. Figure 2 illustrates this concept.

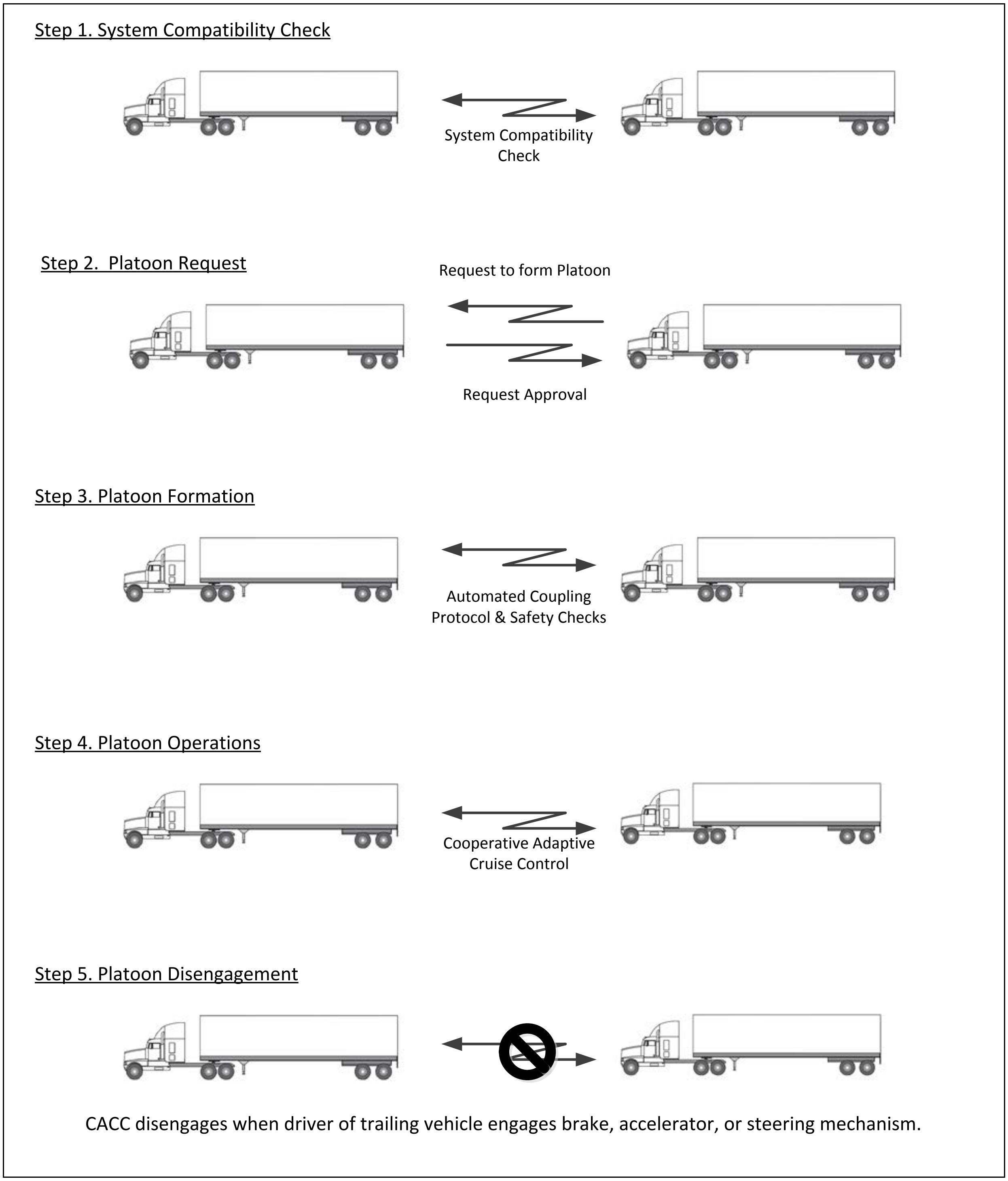


Figure 2. Illustration of Ad Hoc On-the-Fly Platooning Concept.

In this alternative, the two trucks would be completely independent of one another and the system would be responsible for ensuring that the two vehicles have the compatible hardware and software that would make platooning possible. This concept would allow unaffiliated vehicles (i.e., vehicles without prior arrangements and/or not scheduled by a fleet management center or private service provider) to form platoons and disengage completely at random.

Under this alternative, no exchange of trip information would occur between the vehicles, so there is no control over how far trucks would travel together in a platoon. The only requirement is that the two vehicles have compatible systems for operating as a platoon. Furthermore, platoons may form and dissipate anywhere that automated platooning is permitted. Table 10 summarizes additional advantages and disadvantages associated with this alternative for truck platooning.

Table 10. Advantages and Disadvantages to Ad-Hoc On-the-Fly Platooning.

Advantages	Disadvantages
• Does not require vehicles/ drivers to predefine trip. • No restrictions on type of cargo within the permitted cargo types. • Trucks can form platoons on as needed basis, requires little oversight. • Drivers can perform role of platoon service provider (PSP) and link without prior arrangements.	• No requirement for second truck to switch with first. The second truck gets all benefits without a clear means of brokering the benefits. • Difficulty maintaining equipment compatibility. • More challenging to perform pre-platooning system checks. • Difficulty for TxDOT to regulate who can form platoons (when, where, and why) or designate specific zones where platoons can be formed. • May get pairing of incompatible cargos (i.e., two types of cargos that, if involved in accident, could be potentially hazardous). • Difficult to designate to other vehicles that trucks have formed a platoon/operating in tandem. • Might require higher level of automation/communications/ security to accomplish.

Guided On-the-Fly Platooning

This concept is similar to the Ad Hoc On-the-Fly Platooning concept except that instead of the vehicles randomly forming platoons, compatible vehicles are guided to meet with one another while in transit. Under this alternative, a fleet operations center or a PSP would monitor the trucks entering a controlled section of highway where platooning is permitted. Upon entering the controlled areas, trucks would notify the fleet operations center that they are looking to form a platoon for a particular distance. The fleet operations center would then look at all the other trucks in close proximity to the requesting trucks to determine whether a suitable match (i.e., another truck with compatible platooning system with similar origin/destination or trip requirements) is available to participate in a platoon. Platooning vehicles could be from the same company or could be independent operators that are managed by the fleet operations center (i.e., subscribers that receive platooning services from the fleet operations centers). The fleet operations center is responsible for performing the compatibility check between the pairs of vehicles and for approving platooning requests. The fleet operation center would also be responsible for sending messages to each vehicle with information that would allow the matched vehicles to locate each other. The two operators would be responsible for maneuvering their vehicles in the traffic stream in order to allow the automated coupling protocols to activate. Once the vehicles have completed the coupling protocols, the LVs and FVs would operate in a CACC mode.

Figure 3 provides an illustration of this concept. Table 11 provides a summary of the advantages and disadvantages associated with this type of platooning alternative.

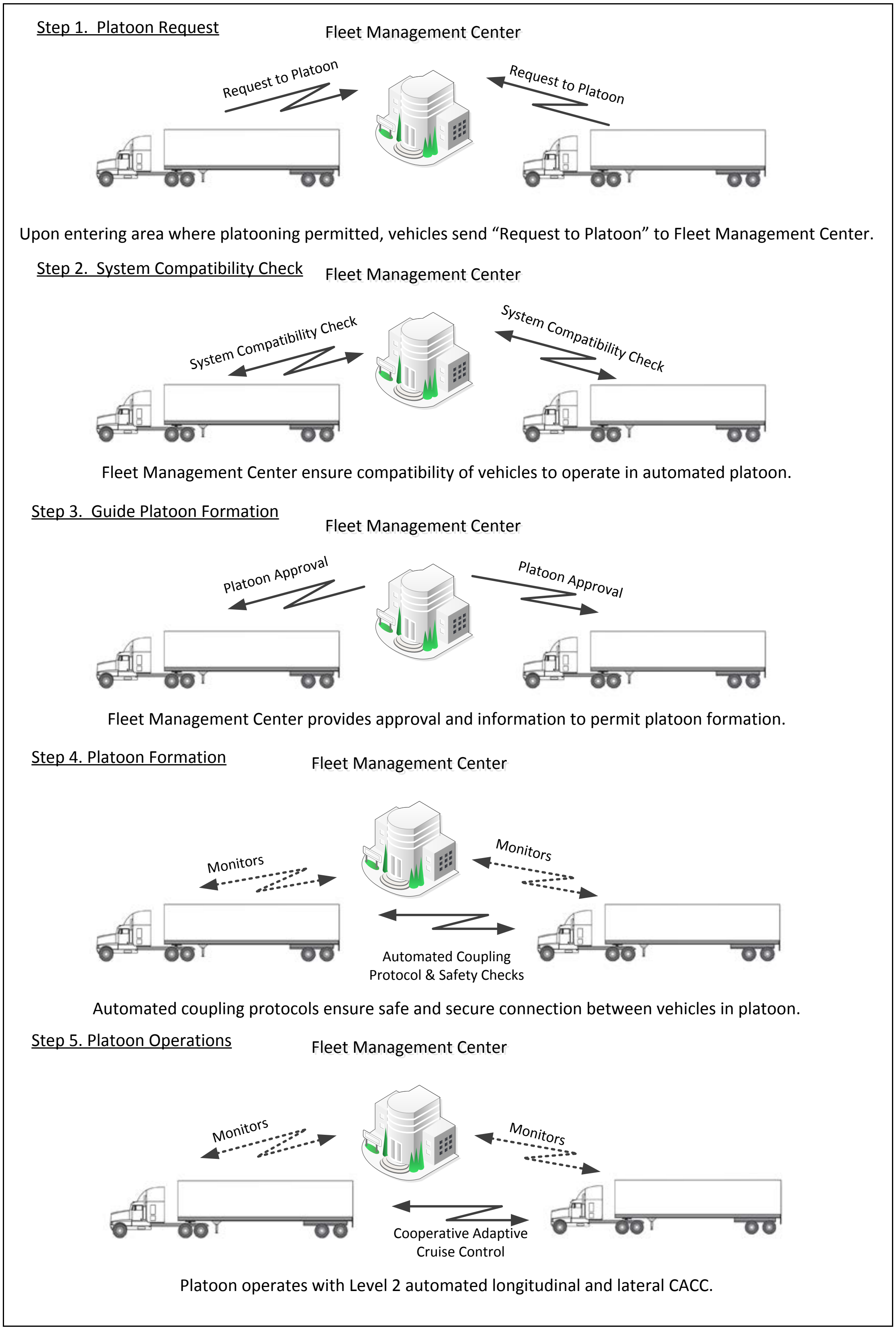


Figure 3. Illustration of Guided On-the-Fly Platooning Concept.

Table 11. Advantages and Disadvantages to Guided On-the-Fly Platooning.

Advantages	Disadvantages
• Platooning vehicle can be identified on-the-fly while vehicles are in transit, minimizing wait time to form platoon (1 to 2 minutes apart). • Dispatch center/service provider responsible for ensuring system compatibility. • Vehicles do not necessarily have to be from same company to participate. • Service provider facilitates determination and payment of any compensation ($ based on fuel savings, $ to cover cost of additional insurance, etc.) from follower to leader.	• Dispatch center/service provider would need to know information about trips to match potential vehicles. • Vehicles would either have to be from same fleet or subscribe to private service provider in order to participate.

Scheduled Platooning

Under this concept, the platooning of two commercial vehicles would be scheduled either through a commercial fleet vehicle dispatching center or through a private service provider that would be responsible for matching subscriber commercial vehicles and participating vehicles would be pre-certified by the commercial fleet operator or the service provider to be able to participate in a platooning operation. The dispatch center or private service providers would identify potential matches for platooning based on common origin/destinations, trip lengths, and desired departure or arrival times. As part of this pre-certification process, the dispatch center would be responsible for also performing and verifying system compatibility between potential matched vehicles. Once a match is found, the dispatch center would then identify a rally point and time at which the two matched vehicles would meet. Scheduled rally points could be on right-of-way (e.g., at safety centers or public rest/picnic areas) or off right-of-way (i.e., distribution centers or private truck stops/fueling stations). The vehicles would then leave the rally point together, but uncoupled. Once at highway speeds, the vehicles would then go through the coupling process for operating in a coordinated platoon.

Figure 4 illustrates the scheduled platooning concept. Vehicles would need to be at least 5 minutes from the rally point in order to allow the service center or the fleet dispatching center sufficient time to locate a nearby vehicle and perform the system compatibility checks. Table 12 describes the advantages and disadvantages of scheduled platooning.

Table 12. Advantages and Disadvantages to Scheduled Platooning.

Advantages	Disadvantages
• Ensure compatible cargos. • Equipment compatibility can be checked before needing to form platoon. • Drivers could prearrange who would lead and who would follow/ rules for trading off LV. • Companies could regulate who could platoon with whom. • Location of platoon formation known, but not necessarily dissolution point. • Can use independent PSP as means of forming platoons.	• Require trucks to predefine need for platooning. • Limits flexibility for forming platoons. • DOT could regulate where platoons form but not where they dissolve.

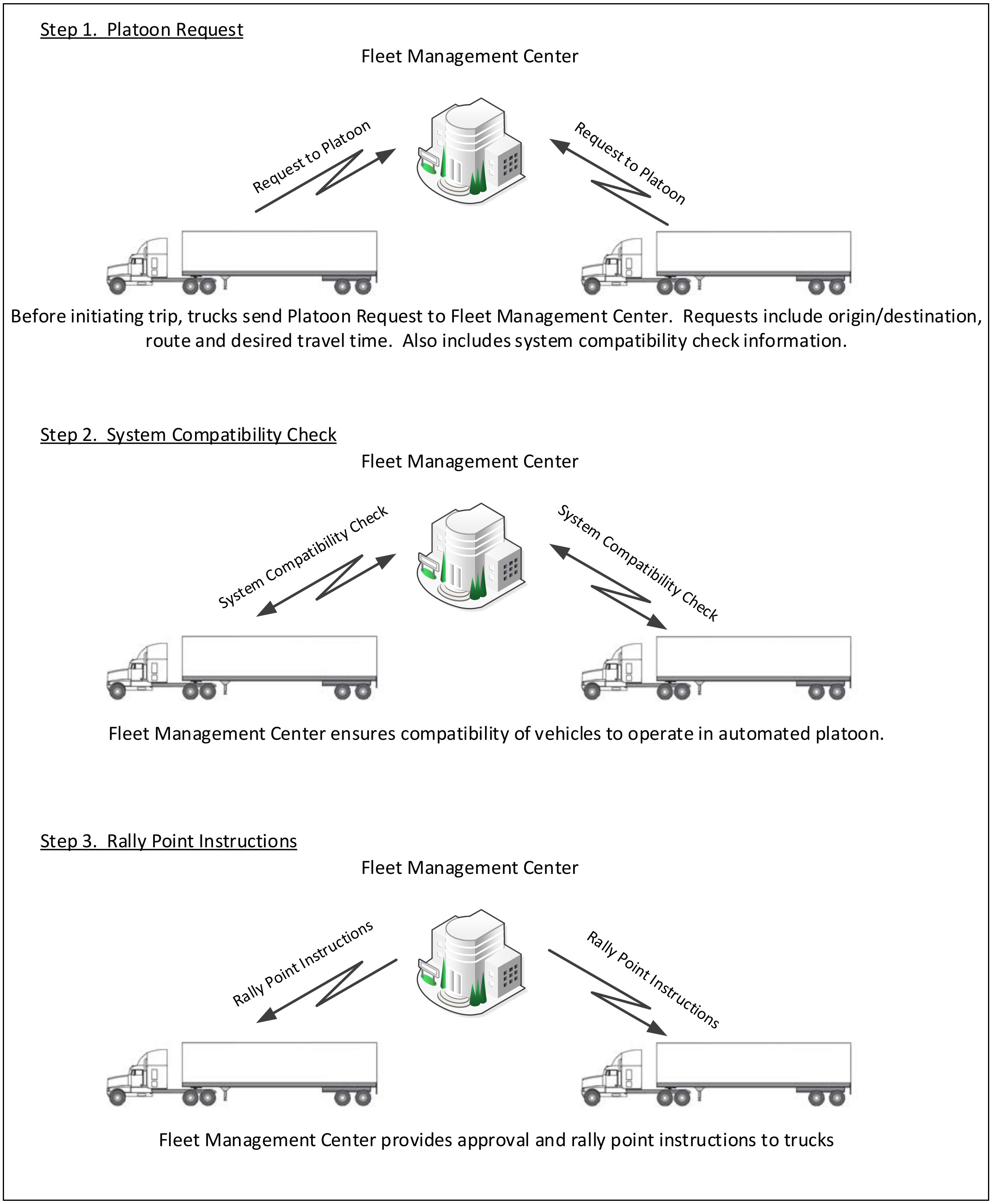


Figure 4. Illustration of Scheduled Platooning Concept.

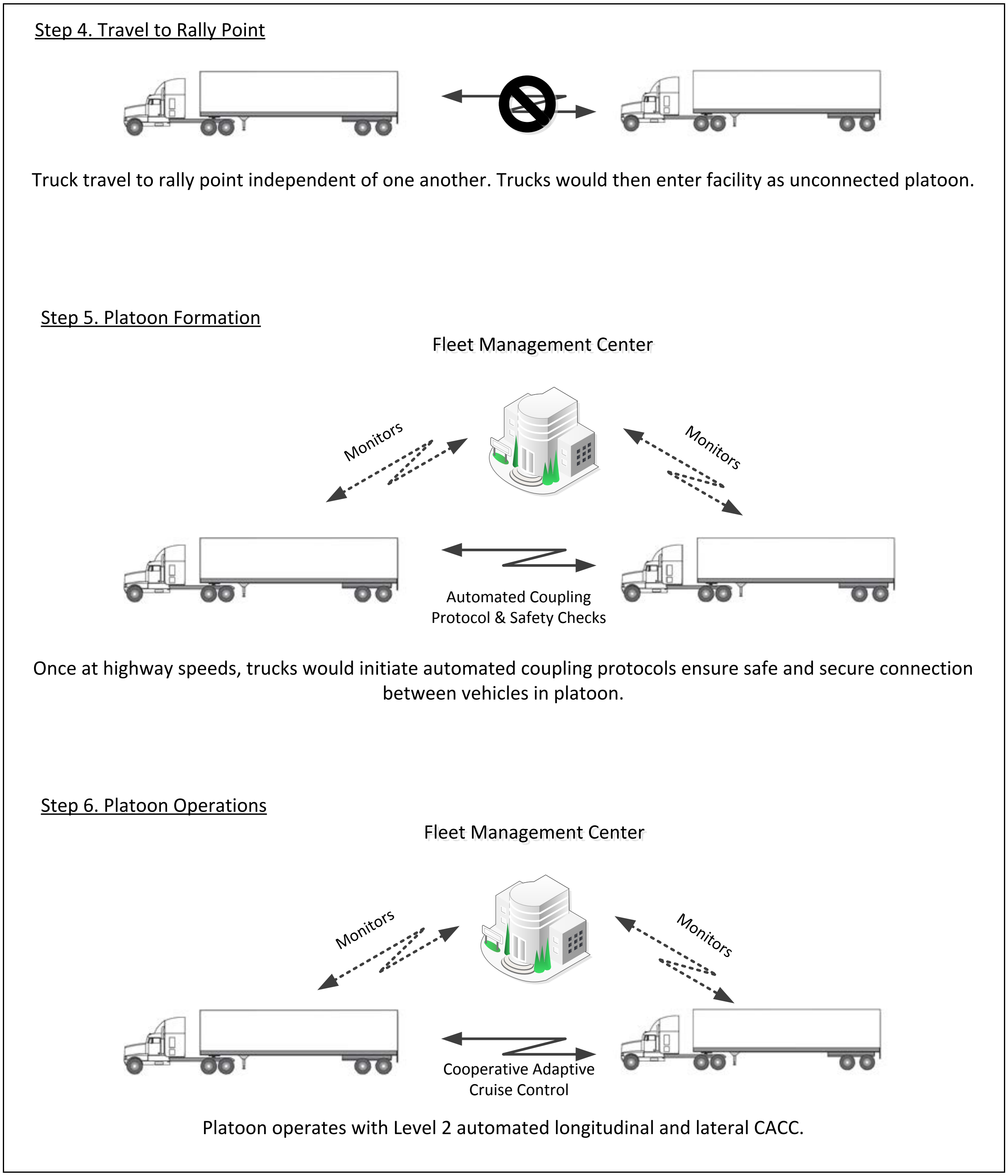


Figure 4. Illustration of Scheduled Platooning Concept. (Continued).

Trip Platooning

Trip platooning is the last of the concepts identified as part of this project. The trip platooning concept is similar to the scheduled platooning concept except that instead of matching while the vehicles are in transit, platoon matches are made before the trips begin. Under the trip platooning concept, a fleet dispatch center (or private service provider) would prearrange for vehicles to travel in a platoon together. The vehicles would meet and/or leave a distribution center or a port of entry at the same time and travel as an unconnected platoon until they reach a pre-designated roadway segment where platooning is permitted. Once up to highway speeds, the matched vehicles would proceed with the coupling protocols and form the automated platoon. The vehicles would then travel in a platoon until they reach their predetermined disengagement point on the facility, at which time the drivers of the two vehicles would activate protocols for disengaging the automated platoon. For long trips, the fleet operator/service provider could schedule the vehicles to switch positions (the LV becomes the FV) at predefined points along the trip.

Figure 5 illustrates the trip platooning concept, while Table 13 provides a summary of the advantages and disadvantages of the trip platooning alternative.

Table 13. Advantages and Disadvantages to Trip Platooning.

Advantages	Disadvantages
• Companies can ensure equipment compatibilities. • DOT can regulate companies allowed to participate in platooning. • DOT can hold any company accountable for abuses of the system. • Pre-scheduled departure times might increase efficiency of the distribution center operations. • Any compensation mechanisms between different companies are easier to implement.	• Company receives benefits of platooning (not independent driver). • Requires truck from same company to share same route at least for designated portion of trip. • Requires trucks to be on same scheduled departure for distribution center. • Denies other compatibly equipped trucks from other companies from platooning opportunities.

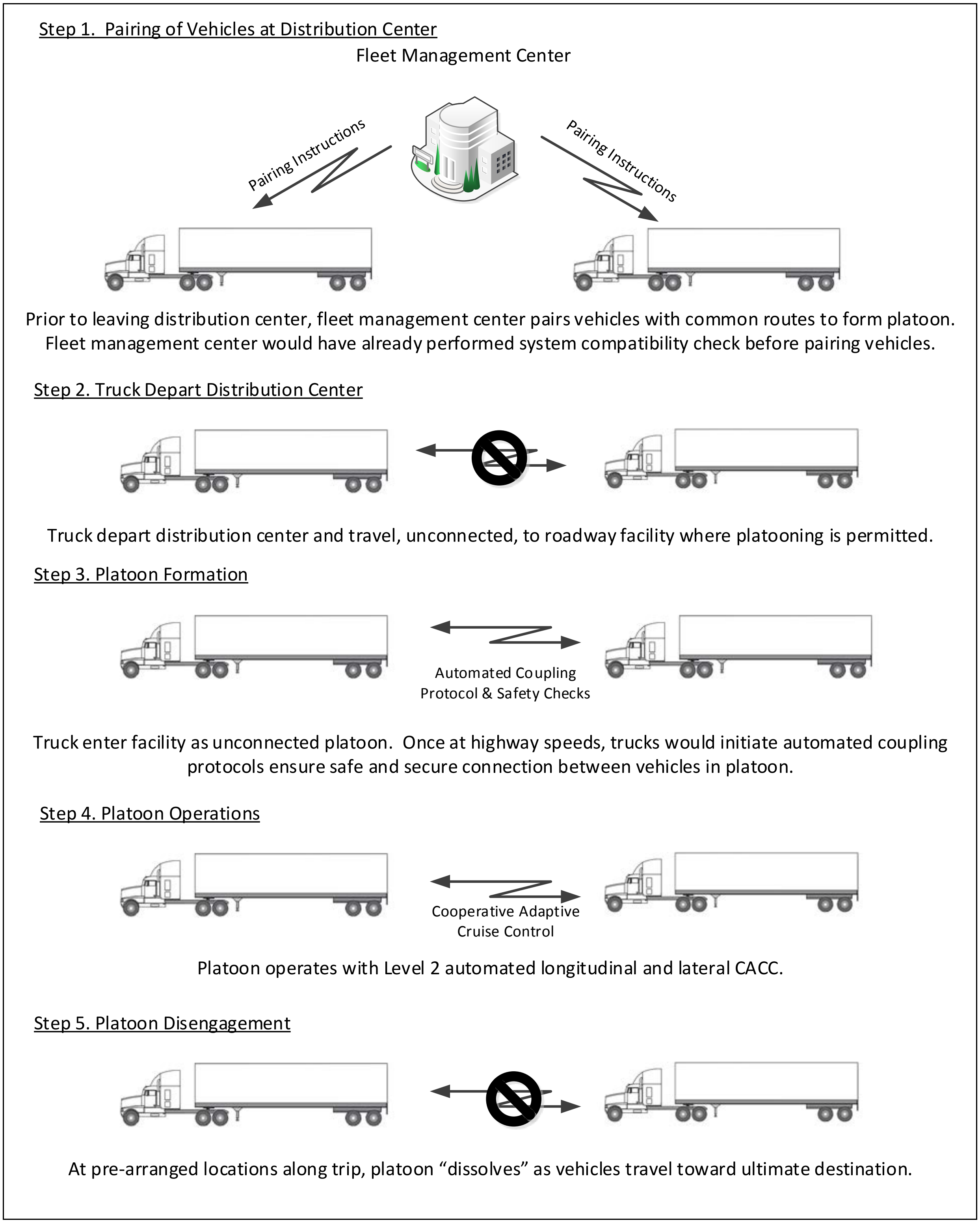


Figure 5. Illustration of Trip Platooning Concept.

Platoon Service Provider

Critical to almost all but the Ad Hoc On-the-Fly alternative is an entity referred to as PSP. This PSP entity can be a public or third-party entity that is responsible primarily for identifying vehicles and coordinating the formation of platoons. This entity could be a dispatch center for a commercial fleet operator, but is more likely to be a third-party entity that specializes in providing services for all types of commercial fleet vehicle operators (including assisting in identifying vehicles to participate in truck platoons). The PSP would act as an intermediary between various commercial vehicle operators and would be responsible for identifying vehicles to participate in platoons on the roadway. To do so, the PSP would use detailed information about route schedule and transport plans provided by commercial vehicle operators to organize and orchestrate when and where vehicles would meet in order to form platoons. Part of the responsibility of the PSP would be to perform system compatibility checks of those vehicles that would participate in the platooning efforts. The PSP might also be responsible for performing administrative functions associated with operating a truck platooning program, including:

- Identifying and certifying commercial vehicles for participation in platooning programs.
- Checking the compatibility of commercial vehicle platooning equipment.
- Ensuring insurance requirements are met by commercial vehicle operators.
- Ensuring driver training requirements.
- Managing and monitoring of vehicles in route to their destinations.
- Providing equitable distribution of benefits.
- Ensuring vehicles are up-to-date on required inspections.

Table 14 shows potential advantages and disadvantages of using the PSP to assist in formulating and managing truck platoons.

Table 14. Advantages and Disadvantages Associated with Using Platoon Service Provider.

Advantages	Disadvantages
• Ensures that only qualified vehicles/drivers participate in platooning. • Independent owner-drivers and small owner-operators can participate. • Smaller agencies with limited equipped fleet vehicles can participate. • Maintains level of quality control over companies participating in the program. • Performs administrative duties for platooning activities (coordinating schedules, arrange insurances, coordinating compatible loads, etc.). • Could potentially designate specific routes and/or lanes for platoons with designated waypoint times (windows) to ensure continuous freight movement.	• Requires companies to file detailed routing schedules. • Free rider problem where small companies with minimal investments can take advantage of platooning opportunities offered by large companies with much more substantial investment. • Companies have less control over platooning policy or may be compelled to pay premium to PSP for priority in scheduling/partnering. • Lack of platoon schedule during off-hours or hours when PSP does not operate.

DEFINE PERFORMANCE MEASURES

In the following sections, the research team identifies the characteristics of the roadways where truck platooning might be implemented.

Ideal Roadway Characteristics

In the initial deployments of truck platooning concepts, platoons shall be permitted only on limited access, multilane facilities (or exclusive lane facilities) where the level of service (LOS) is C or better and the travel speeds consistently range between 55 mph and 75 mph. Once engaged, the platooning system must be capable of operating at speeds between 30 mph and 75 mph. Later deployments may include the ability for the systems to use stop-and-go ACC capability to allow the vehicles to come to a complete stop, and then automatically resume longitudinal control in congested traffic.

The following list provides the recommended ideal roadway characteristics under which truck platooning would be permitted in Texas:

- The roadway should be classified as an interstate or divided multilane highway with at least 2 or more lanes in each direction with no median cross-over used by traffic.
- The general operating speeds are in excess of 60 mph during the majority of the day.
- At least 0.5-mile spacing (desirable) between ramps (entrance and exit ramps). The minimum distances between different ramp configurations as dictated by TxDOT *Roadway Design Manual* (*89*) are as follows:

- Entrance ramp followed by exit ramp: 2000 ft (w/o aux. lanes), 1500 ft (w/ aux. lanes).
- Exit ramp followed by exit ramp: 1000 ft.
- Exit ramp followed by entrance ramp: governed by geometrics of the connections to the adjacent roadway or connecting roadway.

- The roadways should operate a LOS C or better (density < 26 pcpmpl) during times when truck platooning is permitted.
- The roadway should be located on relatively level terrain with no sustained grades > +3 percent.
- The width of the primary travel lanes should be 11 ft or more throughout the entire section where truck platooning is to be deployed.
- The roadway should have a continuous inside shoulder of at least 4 ft in width and an outside shoulder of at least 10 ft.
- The pavements should be maintained in good state of repair with limited rutting, warping, and subsurface damage.
- Radii for all horizontal curvature should be above usual minimum.
- The roadway should be free of any horizontal obstructions that may block sight distance around horizontal curvatures. Horizontal curves should be designed with at least a 60 mph design speed.
- The roadway should provide the recommended decision sight distance to safely execute a speed/path/direction change on rural roads. For rural highways, Table 15 shows the recommended decision sight distances different roadway with different designs speeds.

Table 15. Decision Sight Distance Required for Avoidance Maneuver (*89*).

Decision Sight Distance (ft) Avoidance Maneuver		
Design Speed (mph)	Urban	Rural
60	990	1280
65	1050	1365
70	1105	1445
75	1180	1545
80	1260	1650

Exclusive Truck Platooning Lanes

TxDOT may also want to consider implementing special lanes where truck platooning would be permitted. If so, TxDOT would likely begin by establishing criteria for such lanes so that the concept is uniformly applied. These would be lanes dedicated to the exclusive use of truck platooning. These roadways could be normal lanes that would be dedicated for use by truck platoons at night on intercity divided rural highways. These could also be HOV/managed lanes at night or off-peak in urban areas. Furthermore, certain sections or lanes could be also designated for through platoons only (traveling entire distance of dedicated lane) in order to improve freight flow through an urban area. In these situations, TxDOT may wish to open the shoulder to passenger vehicles and require trucks to operate in leftmost (or inside) lane.

Table 16. Advantages and Disadvantages of Exclusive Truck Platooning Lanes.

Advantages	Disadvantages
• Separates platoons from normal traffic. • Makes better utilization of existing roadway capacity. • Takes advantage of similar operational capabilities of trucks in separated traffic.	• Reduces available capacity of roadway and operational flexibility for non-platooned vehicles (cars and other trucks). • Enforcement of hours of operation/designated lanes is required. • Requires special incident management to keep lanes open. • Public opinion problem at times when truck-only lane is unused when general purpose lanes are congested with traffic.

Performance Measures

TxDOT should use both basic system performance data and effectiveness data to assess the overall performance of truck platooning on traffic operations. Basic system performance data involves collecting data on the basic operations of the system and would include information such as the following:

- Number of collisions involving truck platoons (total and by severity category).
- Number of collisions involving automobiles and trucks not in platoons (total and by severity category).
- Number of truck miles traveled in platoons.
- Average number of platoon disengagements/re-engagements per trip/mile, etc.
- Average duration of disengagement.
- Ratio of time disengaged to time engaged per trip.
- Locations of segments and times where platoons forced to disengage.
- Number of total vehicle miles traveled in the corridor (both automobile, trucks not in platoons, and trucks in platoons).
- Percent of trucks traveling in platoons and not operating in platoon.
- Number of hours per day/percent of hours per week in which truck platooning was active.

In addition to tracking basic performance statistics on the operation of the system throughout the deployment, performance data will also be collected to assess the effectiveness of the truck platooning alternatives. Table 17 shows the proposed measures of effectiveness that would be used by the research team to assess the effectiveness of deploying truck platooning in various corridors. The effectiveness of truck platooning will be evaluated in the following categories:

- Safety.
- Mobility.
- Capacity/throughput.
- Environmental.
- Infrastructure preservation.
- Customer satisfaction.

The research team anticipates using a before/after comparison to evaluate the effectiveness of the truck platooning in the deployment corridor. For this analysis, the before data would represent conditions prior to allowing trucks to operate in platoons in the corridor while the after data would represent travel conditions in the corridor after allowing trucks to operate as platoons in the corridor.

Table 17. Proposed Measures of Effectiveness for Evaluating Truck Platooning Alternatives in Texas.

Category	Measures of Effectiveness
Safety	• No significant increase in overall crash rates in the corridor. • No significant increase in the number of truck/automobile collisions. • No significant increase in the number of severe (K,A) collisions involving trucks or caused by truck platoons in the corridor.
Mobility	• Significant increase in the number of trucks (as percent of average annual daily traffic [AADT]) in corridor. • No significant change in automobile travel time times/travel speeds through the deployment corridor. • No significant change in truck travel times/travel speeds through the deployment corridor. • No significant change in travel time variability of automobiles traveling through the deployment corridor. • Significant change in travel time variability of truck traveling through the deployment corridor.
Capacity/ Throughput	• Significant increase in the effective capacity[9] in the deployment corridor. • Significant change in the vehicle throughput through the deployment corridor. • Significant increase in the freight throughput[10] through the deployment corridor.
Energy & Environment	• Significant reduction in truck emissions in the deployment corridor. • Significant reduction in truck fuel consumption in the deployment corridor.
Infrastructure Preservation	• No significant increase in pavement damage in the deployment corridor. • No significant detrimental impact to bridge structures in the deployment corridor.
Customer Satisfaction	• No significant negative subjective feedback from automobile users. • Positive subjective feedback from commercial vehicle operators (drivers). • No significant negative subjective feedback from TxDOT district operations and maintenance personnel. • No significant negative subjective feedback from state/county/local elected officials. • Positive subjective feedback from commercial fleet operators.

IDENTIFY SUITABLE SITES/CORRIDORS

As part of the research effort, the research team identified potential sites or corridors for commercial truck platooning in Texas where truck platooning may benefit both TxDOT and fleet operators. In identifying the potential candidate test bed sites, the research team applied the following criteria:

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[9] *Effective capacity* is the maximum potential rate at which persons or vehicles may traverse a link, node, or network under a representative composite of roadway conditions. Capacity, as defined by the Highway Capacity Manual (HCM), is: "maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a given point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions." The major difference between effective capacity and capacity, as defined by the HCM, is that capacity is assumed to be measured under good weather and pavement conditions and without incidents, whereas effective capacity can vary depending on these conditions and the use of management and operations strategies such as ITS. See more at: http://www.its.dot.gov/evaluation/eguide_resource.htm#sthash.KaYERPSU.dpuf.

[10] Throughput is defined as the number of persons, vehicles, or units of freight actually traversing a roadway section or network per unit time. Increases in throughput are sometimes realizations of increases in effective capacity. See more at: http://www.its.dot.gov/evaluation/eguide_resource.htm#sthash.KaYERPSU.dpuf.

- Facility Type: Freeways (primarily interstate highways) located outside major urbanized or highly developed areas.
- Daily Traffic Volume: (suggest a range in vehicles per day (vpd)) Relatively low AADT to ensure that roadways will operate at a high LOS during the majority of the day.
- Daily Truck Volume: A 24-hour truck percentage of at least 15 percent.
- Minimum Length of Test Corridor: Relatively long stretch of highway should exist between urban centers to ensure that platooning would be appropriate
- Speed Limit Range: The posted speed limit should be 65 mph or greater.

Figure 6 shows the location of the major urbanized areas in Texas. West Texas and the Panhandle have the fewest urbanized areas in the state, with travel distances greater than 100 miles separating most of the major urban areas. Urban areas tend to be located closer in the eastern and central section of Texas, which reduces the likelihood of finding long stretches of highways interrupted by urbanized areas.

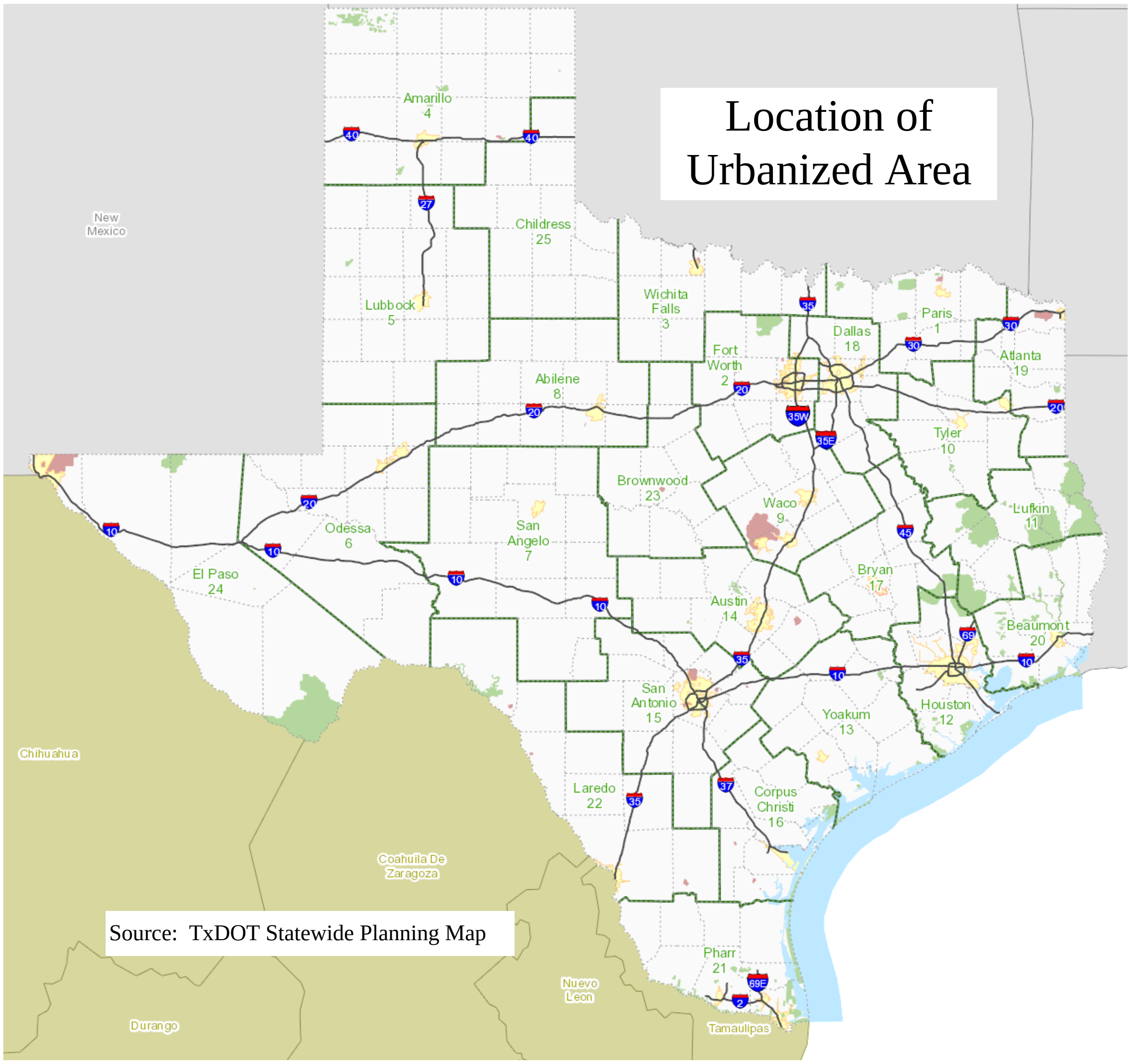


Figure 6. Locations of Urbanized Areas in Texas.

Figure 7 shows the AADT on different section of interstates in Texas. I-35, I-45, and I-10, between San Antonio, Dallas/Fort Worth, and Houston generally have the highest AADT in the state, while I-10 and I-20 in West Texas, I-40 and I-27 in the Panhandle, and I-35 and I-37 in South Texas experience relatively low to moderate AADTs. I-10 between Houston and the Louisiana border generally has the highest rural AADT in the state.

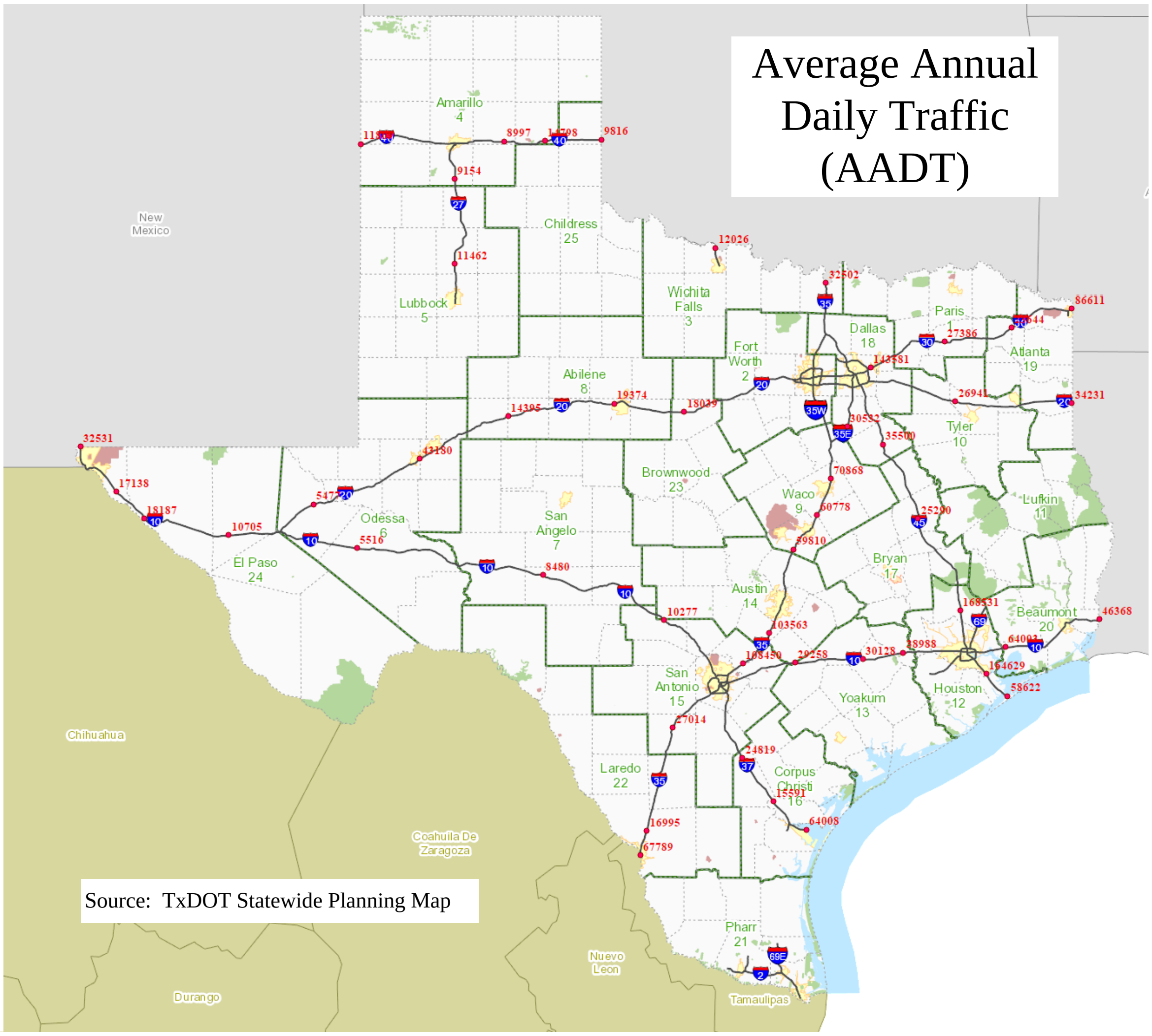


Figure 7. AADT on Rural Interstate Roadways in Texas.

The research team identified the percent of truck traveling in the traffic stream as a critical factor in selecting candidate test bed sites. The research teams assumed that the opportunities for trucks to form platoons would be higher on roadways that experience a higher percent of trucks. Figure 8 shows the interstate roadways that experience more than 15 percent, 20, percent, 30 percent, and 40 percent truck traffic. The figure shows the highest percentage of trucks traveling in West Texas, the Panhandle, far East Texas, and in the Gulf Coast regions of Texas. Trucks represent over 40 percent of the daily traffic on I-40 in the Panhandle, on I-10 and I-20 in West Texas, and on I-30 in East Texas.

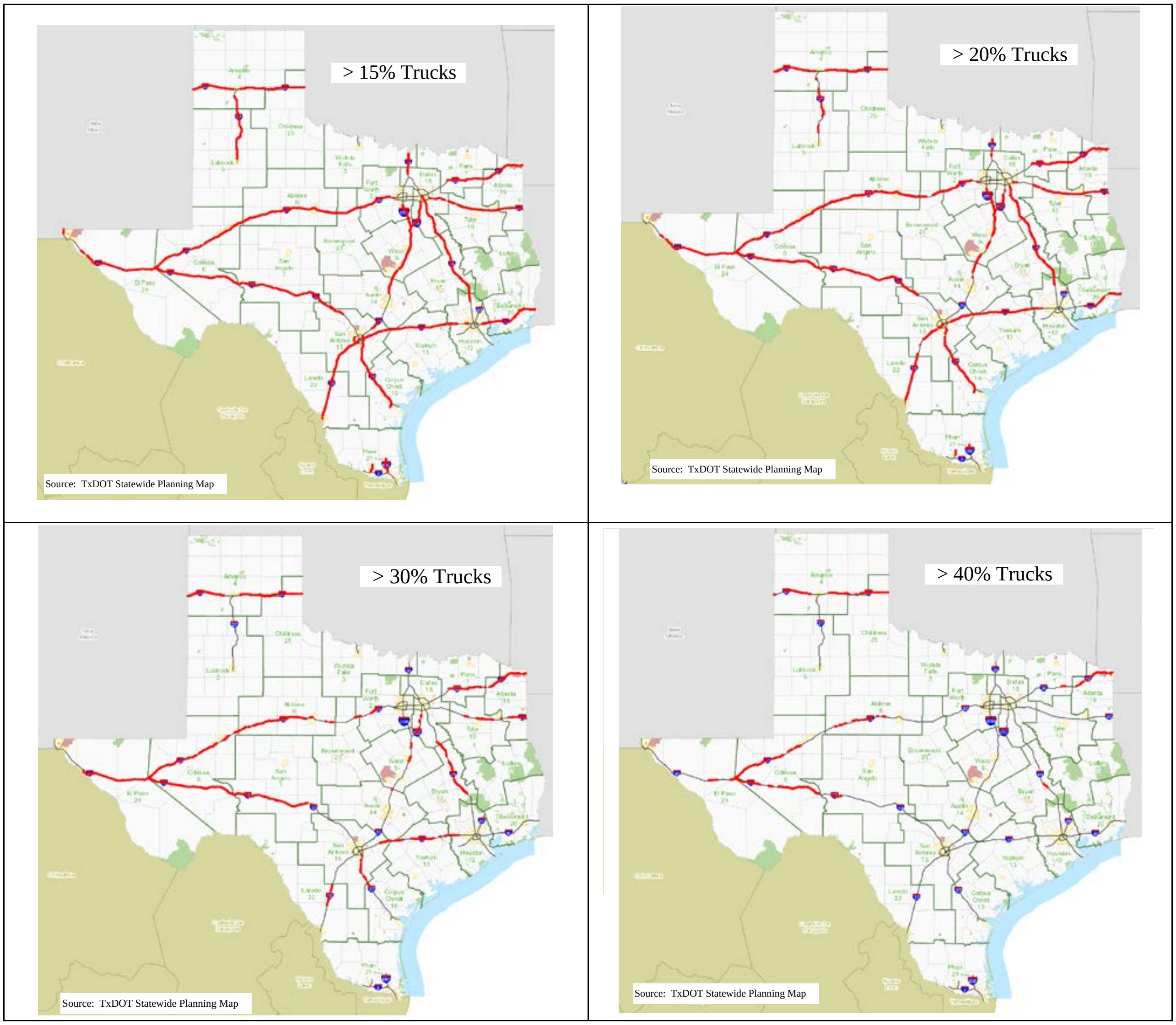


Figure 8. 24-Hour Percentage Trucks on Interstate Facilities in Texas.

Figure 9 shows the posted speed limits on various sections of interstate highways in Texas. In selecting potential test bed locations, the research team focused on interstate highways that have posted speed limits of 65 mph or more. Note the speed limit on both I-10 and I-20 in West Texas is 80 mph while in most other locations in Texas the posted speed limit on interstate facilities is 75 mph. Speed limits on the interstate system decrease to 60 mph or lower near many of the major metropolitan areas, such as Houston, Dallas, San Antonio, Austin, and others.

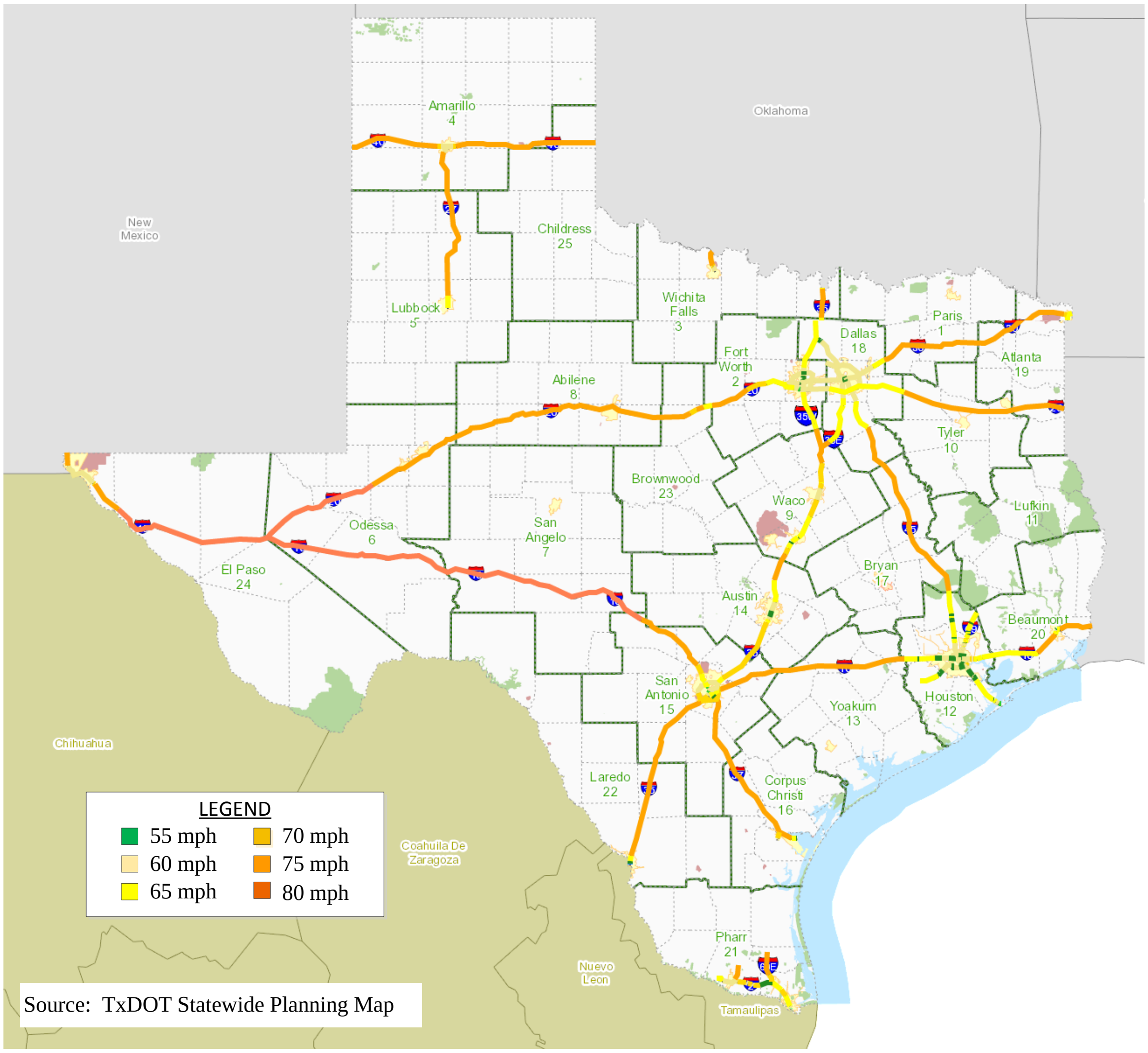


Figure 9. Posted Speed Limits on Interstate Facilities in Texas.

Table 18 shows those sections of interstate highways identified by the research team as being potential test bed sites for demonstrating truck platooning concepts in Texas. Figure 10 shows the approximate location of these sites. Additional field studies are needed to verify that these locations conform to the criteria described in the ideal roadway characteristics above.

Table 18. Potential Test Bed Locations for Demonstrating Truck Platooning in Texas.

Roadway	Limits	Milepoints		Length (miles)	AADT	% Trucks	Speed Limit (mph)	Number of Lanes	TxDOT District(s)
		Beginning	Ending		Average	Average			
IH0010	East of El Paso to IH10/IH20 Split	45	186	141	15195	36.7	75/80	4	El Paso
IH0010	IH10/IH20 Split to West of Fort Stockton	188	256	68	5454	42.5	80	4	Odessa
IH0010	East of Fort Stockton to Sonora	262	400	138	6022	40.6	80/75	4	Odessa/San Angelo
IH0010	Sonora to West of Kerrville	401	505	104	9404	27.4	75	4	San Angelo/Austin/San Antonio
IH0010	East of Kerrville to East of Boerne	511	537	26	19391	11.9	75	4	San Antonio
IH0010	East of Schertz to West of Seguin	592	603	11	33984	22.9	75	4	San Antonio
IH0010	East Seguin to West of Sealy	616	716	100	31190	32.7	75	4	San Antonio/Austin/Yoakum
IH0010	Baytown to Beaumont	800	945	145	51228	22.1	65/75	4	Beaumont
IH0020	East of IH10/IH20 Split to Odessa	1	104	103	9386	45.8	75/80	4	Odessa
IH0020	East of Midland to West of Abilene	146	276	130	17249	36.0	75	4	Abilene/Odessa
IH0020	East of Abilene to West of Weatherford	295	404	109	21231	26.9	75/70/65	4	Abilene/Brownwood
IH0020	East of Terrell to Louisanna Border	504	630	126	30823	30.3	65/75	4	Tyler/Atlanta
IH0027	South of Canyon to North of Plainview	106	55	51	8987	21.0	75	4	Amarillo/ Lubbock
IH0027	South of Plainview to North of New Deal	45	16	29	12250	18.1	75	4	Lubbock
IH0030	East of Greenville to West of Sulphur Springs	99	121	22	28966	34.7	75	4	Paris
IH0030	East of Sulphur Springs to West of Mout Pleasant	128	160	32	25398	30.8	75	4	Paris
IH0030	East of Mount Pleasant to West of New Boston	164	200	36	24378	38.1	75	4	Atlanta
IH0035	North of Laredo to South of Pearsall	15	98	83	22292	24.0	75	4	Laredo/San Antonio
IH0035	North of Pearsall to South of San Antonio	102	148	46	32252	25.9	75	4	San Antonio
IH0035	North of Georgetown to South of Salado	267	284	17	61321	29.2	75	6	Austin/Waco
IH0035	North of Temple to South of Robinson	306	327	21	63739	22.5	65/70	4/6	Waco
IH0035	North of Lacy-Lakeview to South of Hillsboro	343	363	20	56672	28.7	75/65	4/6	Waco
IH0035E	North I35E/W Split to South of Waxahachie	372	397	25	32291	32.4	75/65	4	Waco/Dallas
IH0035W	North I35E/W Split to South of Alvarado	1	23	22	24660	23.7	75/65	4	Waco/Fort Worth
IH0037	North of Corpus Christi to South of San Antonio	18	127	109	23772	25.0	75	4	Corpus Christi/San Antonio
IH0040	New Mexico Border to West of Amarillo	0	60	60	11043	37.0	75	4	Amarillo
IH0040	East of Amarillo to Oklahoma Border	86	176	90	10487	45.1	75	4	Amarillo
IH0045	South of Richland to North of Huntsville	218	121	97	26945	35.4	75	4	Dallas/Bryan
IH0045	South of Huntsville to North of Willis	112	98	14	42110	21.1	65	4	Bryan/Houston

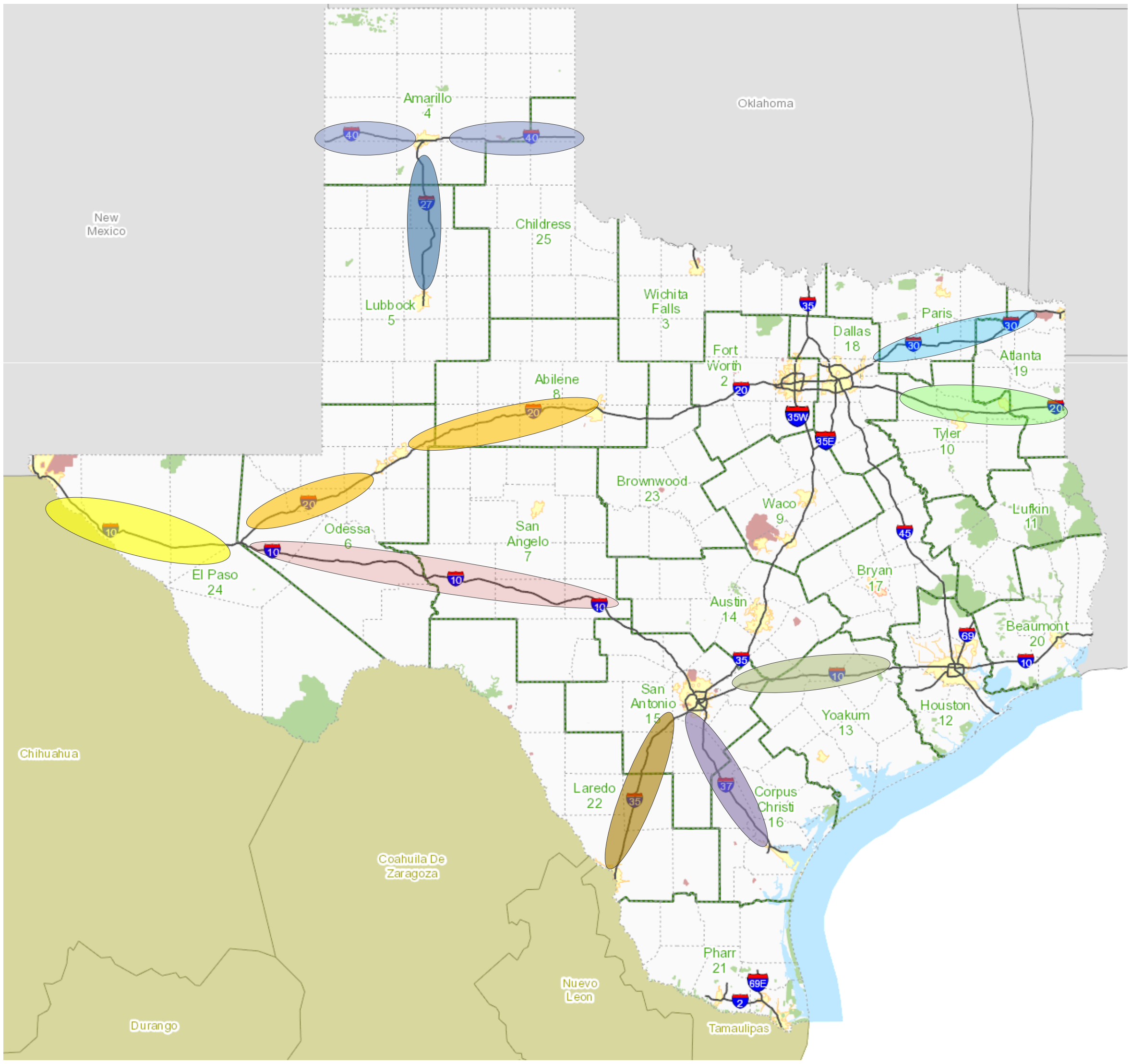


Figure 10. Candidate Test Bed Site Locations for Demonstrating Truck Platooning in Texas.

IDENTIFY ORGANIZATIONAL ISSUES

The research team identified and characterized organizational issues that must be addressed prior to implementing a truck platooning system. The research team met with trucking industry representatives, law enforcement officials, and the TxDOT division and district personnel to identify potential issues from their perspectives. To facilitate the identification of organizational issues, the research team asked representatives from these agencies and organizations a series of open-ended questions on the following topics:

- Appropriate user types and their level of experts.
- Training requirements and constraints.
- Enforcement and traffic incident management procedures.

- Control algorithm and technology needs.
- Roles and responsibilities of operators.

The purpose of these interviews was to examine likely issues impacting the deployment of truck platooning in Texas and to provide preliminary recommendations on how they might be addressed during the implementation phase of this project.

Selection of Interviewees

The stakeholders and experts identified for the interview process include representatives of various perspectives. The categories of agencies selected for interviews include, but are not limited to:

- Trucking industry association representatives.
- Motor carrier safety experts.
- Military (i.e., Army and National Guard).
- Public sector agency representatives (DOTs, DMV, etc.).
- Toll road operators.
- Law enforcement.
- Commercial vehicle platooning and V2V/V2I system suppliers.
- Commercial freight operators (large/medium).
- Owner/operators (small freight operators).
- Drivers.

The interview questions approved by the Texas A&M Institutional Review Board and used to guide the interviews with stakeholders are provided in Appendix C. The questions vary for each of the four stakeholder groups.

Interview Synthesis

The research team conducted 11 stakeholder interviews with truck drivers, fleet owners, government agencies, and trade associations during October and November 2015. Each interview was either conducted in-person at an off-site office location or as a phone conference. The interviews consisted of roughly 9–12 questions that focused on operational-related impacts of truck platooning. This summary reflects a synthesis of the interviewees' perspectives on these issues. The four key topics most commonly discussed, and synthesized in this report, are as follows:

- Operational Benefits.
- Safety Concerns.
- Performance Measures for Analyzing Platooning.

- Minimum Road and Operating Requirements.
- Level of Need for Real-time Information.

Operational Benefits

All of the interviews provided the respondents an opportunity to provide their viewpoint on the operational benefits of commercial truck platooning. Most respondents admitted they had to research truck platooning because their organization was not actively pursuing more knowledge about the technology.

For truck drivers and fleet owners, the responses for operational benefits varied from skepticism about capability to realize any benefits to seeing some benefits in terms of operation. A couple fleet owners mentioned that fuel savings was the primary, observable benefit from equipping trucks with CACC. CACC could keep trucks from unnecessary stopping or accelerating changes because the process to downshift or upshift use fuel. One fleet owner placed a particular emphasis on the ability of such a system to lessen the probability of crashes. A government agency suggested that law enforcement agencies may have an easier time with enforcement. The same government agency also suggested that state departments of transportation could realize better performance due to fewer crashes.

The respondents that expressed skepticism based their opinions on how their fleet operated, with a specific reference on their trip lengths and the type of good shipped. Drivers and owners who made deliveries within a region, or short-range trips, believed they could not realize the any savings. For example, one driver suggested they could save 5–20 percent on fuel savings just by renegotiating the contract with their fuel provider. Some drivers and owners have mentioned that companies prefer to stagger deliveries as opposed to dispatching a platoon (e.g., concrete and construction deliveries). Those drivers also believed that large companies could benefit if their scheduling permitted multiple trucks to travel to the same location at the same time.

Safety Concerns

Interviews expressed various concerns on safety implications of implementing commercial truck platooning. Those concerns tended to focus on driver anxiety of passing vehicles, drivers attempting to merge in the middle of a platoon, and highway hypnosis. Passing vehicles was expressed as an acute concern, particular of two-lane lane roads where vehicles have to spend a considerable about of time traveling in a lane meant for opposing traffic. A few respondents were apprehensive about differences in vehicle power and torque between the vehicles in the platoon. Interviewees asked whether leading vehicle could be more responsive to speed changes than FVs and whether the FV could safely adapt to changes. Many drivers and owners stated that highway hypnosis would become more widespread with the adoption of CACC and that drivers would tend to rely more on their equipment than on their own experience and judgement. Drivers who shipped liquid goods expressed many doubts about CACC providing benefits and were concerned the technology was not capable of handling the complexities of a moving live load during trips. Drivers mentioned they have to constantly adjust steering, acceleration, and braking to account for a fluid that moves back-and-forth, and side-to-side.

Performance Measures for Analyzing Platooning

The potential for fuel savings and fuel efficiency were the most commonly noted performance measure to analyze truck platooning in the interviews. Many respondents thought that fuel savings could be achieved while in platoon from the decreased wind resistance and less frequent acceleration, deceleration, and braking. However, respondents suggested that they would want to know the magnitude of potential fuel savings from truck platooning. Multiple respondents expressed concerns that vehicle, roadway, or traffic conditions might diminish the potential savings and it was important to know if and how much benefit could be achieved. Several respondents were unsure whether platooning would generate enough savings to justify potential costs, safety concerns, or uncertainty. One respondent presented a situation, as an example, in which a car driver cuts into the gap between platooning trucks, forcing the following truck to slow down or disengage and potentially negate any gains in fuel economy or time savings.

Other measures that respondents suggested to analyze platooning were the impact on travel time, possible safety benefits, and the ability of the truck to respond to road conditions. Multiple respondents were interested in how much time could be saved on a platooning trip because this is currently an important performance measure for the trucking industry. Some respondents suggested that there may be safety benefits from platooning, while others wondered if it would create new safety concerns. One concern was whether the platooning technology could read the road as well as a trained, human driver. Trucks are far more sensitive than a passenger car to road features (e.g., hills, curves) and to the contents/load in the van. One respondent suggested that it would be critical for the platooning technology to be connected to the van or trailer because loads move, shift, and react differently than the front of the truck. Some respondents wanted to know how well the truck would understand and how quickly it could react to external conditions on the road (e.g., weather, other drivers).

Minimum Road and Operating Requirements

Most interviewees agreed that there were some minimum requirements for roadway design and operations that would have to be met before truck platooning should be allowed. Urban versus rural conditions, number of lanes, and the presence of construction zones were the most frequent requirements noted in the interviews. Generally, respondents suggested that it was important to understand how well platooning technology would understand and adapt to the design and conditions of a roadway.

A majority of respondents stated that rural roadways were better suited to platooning than urban roads. Roads through urban areas were considered too busy, were likely to increase occurrences of merging by other vehicles and would require more evasive maneuvering by truck drivers. However, multiple respondents also noted that platooning seemed more plausible on multilane roads that provide passing opportunities. Two-lane roads (one lane in each direction) can limit passing opportunities, which may be exacerbated by the presence of trucks in platoon. Several respondents stated that roadways for platooning should have at least two lanes in each direction. Representatives of law enforcement and public agencies suggested that three lanes may be ideal.

Over one-third of the interviewees also believed that construction zones could be a concern for platooning trucks. A law enforcement representative stated that platooning should not be allowed in construction zones at all. Others were concerned with how platooning technology would respond to unexpected slowdowns and queues.

Platooning was seen as more applicable to longer trips, although respondents were not able to provide a minimum trip length. Respondents were concerned that finding and joining a platoon may take time, and a longer trip was more likely to make up for that initial input of time.

Level of Need for Real-time Information

The interviews suggested that roadway conditions and information about other potential platoon vehicles would influence truck platooning decisions. Information about other platoon vehicles was frequently noted during the interviews, particularly among drivers and owners. Multiple respondents reported that they would want to know the destination of other vehicles, the trip distance, and the route they plan to take. Two respondents also wanted to know what other trucks were hauling. Another respondent suggested it was valuable to know whether the other driver is capable and law-abiding.

Traffic and incidents were the most commonly noted roadway information that would be valuable to trucks making platooning decisions. Some respondents also noted weather conditions and work zone information may influence the decision to platoon. One owner pointed out that travel time, and getting to your destination on time, is an important factor in decision-making. This respondent argued that they would need to know that platooning was going to increase travel speed and/or save time.

Several respondents suggested that the information needed for platooning may be an extension of existing and planned information systems for roadways. A federal agency representative pointed out that current goals are to communicate more information on roadways and communicate that information sooner. Another respondent noted that the electronic messaging signs on roadways already give drivers this type of information, but that those alerts would be more useful if they could be transmitted directly to the driver in a truck. Methods to identify trucks under platoon were noted with respect to enforcement needs, as well as to inform other motorists on the road.

Finally, the need for outreach and training was considered important by several respondents. This included consideration of most stakeholders, including the drivers and freight operations, the public agencies, enforcement, and emergency responders. One participant also mentioned the importance of public awareness.

CHAPTER 4: PLATOONING SCENARIO VALIDATION

INTRODUCTION

Commercial truck platooning is a relatively novel concept in Texas and around the country. Platooning enables commercial trucks to safely travel more closely without the worry of collisions together while at high speeds through vehicle automation, leading to a reduction in emissions, fuel consumption, and operational costs. V2V communications and carefully controlled longitudinal (forward speed) and lateral (steering) automation technologies enable the system, and while the technologies are fairly mature, existing technical, economical, and legal issues may prove barriers to deployment.

This chapter addresses concept feasibility research performed as part of the project. Combined with the research documented in the previous chapter, these efforts make up the Feasibility Study/Concept Exploration process outlined by FHWA in the *System Engineering for Intelligent Transportation System* handbook (*90*). Figure 11 shows the process. The process is intended to identify and assess candidate strategies and select the most viable option(s) for further consideration and development. This process identifies a broad range of concepts that satisfy the project need(s). The concepts are compared relative to measures that assess the benefits, costs, and risks of each alternative.

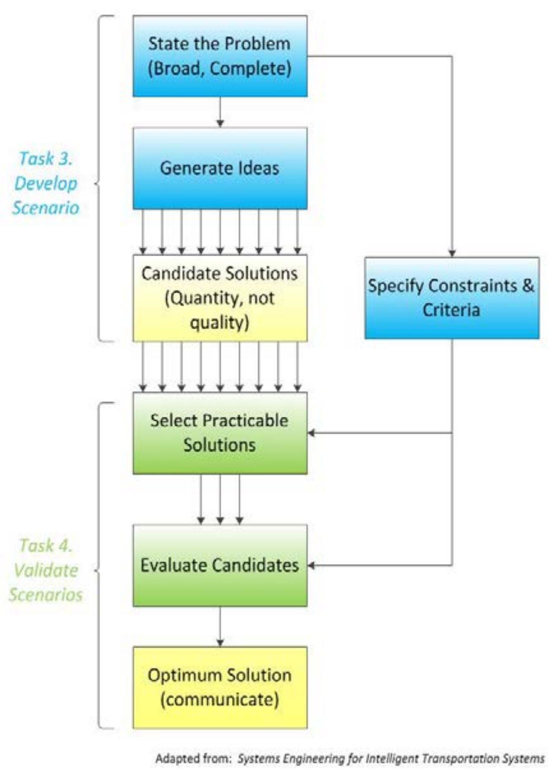


Figure 11. FHWA Feasibility/Concept Exploration Process.

This chapter also summarizes the activities and findings associated with the task on validating platooning scenarios. The task objective was to perform qualitative and quantitative analyses of the alternatives for deploying a truck platooning system in Texas, as identified in a previous task, in order to identify and prioritize two potential future deployment corridors for more detailed Concept of Operations development. For the task, the research team accomplished the following:

- Developed a matrix framework for assessing scenarios and performed the initial qualitative and quantitative analysis.
- Identified suitable applications in relation to identified sites/corridors.
- Performed preliminary simulation to model the impact of application on the environment.
- Initiated cost/benefit analysis for each scenario.
- Initiated planning of the task to choose the scenario(s).

MATRIX FRAMEWORK FOR SCENARIO ASSESSMENT

The research team conducted a thorough qualitative assessment of selected candidate corridors based upon the following general roadway characteristics:

- Interstate roadways or divided multilane roadways with at least two lanes in each direction and no median crossovers.
- Corridors in non-urban settings:
    - Operating at LOS C or better (density < 26 passenger cars per mile per lane (pcpmpl)).
    - Operating at speeds of 60 mph or faster during most of the day and speed limits 55 to 75 mph.
- Rehabilitation not needed near term or scheduled to fit project objectives.
- Air quality rating consistent with project objectives.

The goal of this activity was to develop a framework for assessing the corridors and determine how to compare corridors against each other and determine which of the corridors would be acceptable for use by platoons of commercial vehicles. The investigation used the following criteria:

- Geometric features.
- Infrastructure quality.
- Freight network considerations.

Table 19 summarizes the corridors that are under consideration for this subtask. All sections have two through-lanes in each direction. Figure 12 shows the locations of the candidate corridors.

Table 19. Candidate Corridors for Truck Platooning.

Roadway	Limits	MP		AADT Average	Avg. No. Trucks/Day	Speed Limit (mph)
		Begin	End			
IH0010	East of El Paso to I-10/I-20 Split	45	186	15195	5583	75/80
IH0010	I-10/I-20 Split to West of Fort Stockton	188	256	5454	2319	80
IH0010	East of Fort Stockton to Sonora	262	400	6022	2446	80/75
IH0010	Sonora to West of Kerrville	401	505	9404	2578	75
IH0010	East of Schertz to West of Seguin	592	603	33984	7782	75
IH0010	East Seguin to West of Sealy	616	716	31190	10201	75
IH0020	East of I-10/I-20 Split to Odessa	1	104	9386	4298	75/80
IH0020	East of Midland to West of Abilene	146	276	17249	6212	75
IH0020	East of Terrell to Louisiana Border	504	630	30823	9328	65/75
IH0027	South of Canyon to North of Plainview	106	55	8987	1884	75
IH0027	South of Plainview to North of New Deal	45	16	12250	2217	75
IH0030	East of Greenville to West of Sulphur Springs	99	121	28966	10058	75
IH0030	East of Sulphur Springs to West of Mt Pleasant	128	160	25398	7834	75
IH0030	East of Mount Pleasant to West of New Boston	164	200	24378	9283	75
IH0035	North of Laredo to South of Pearsall	15	98	22292	5341	75
IH0035	North of Pearsall to South of San Antonio	102	148	32252	8342	75
IH0037	North of Corpus Christi to South of San Antonio	18	127	23772	5951	75
IH0040	New Mexico Border to West of Amarillo	0	60	11043	4086	75
IH0040	East of Amarillo to Oklahoma Border	86	176	10487	4731	75

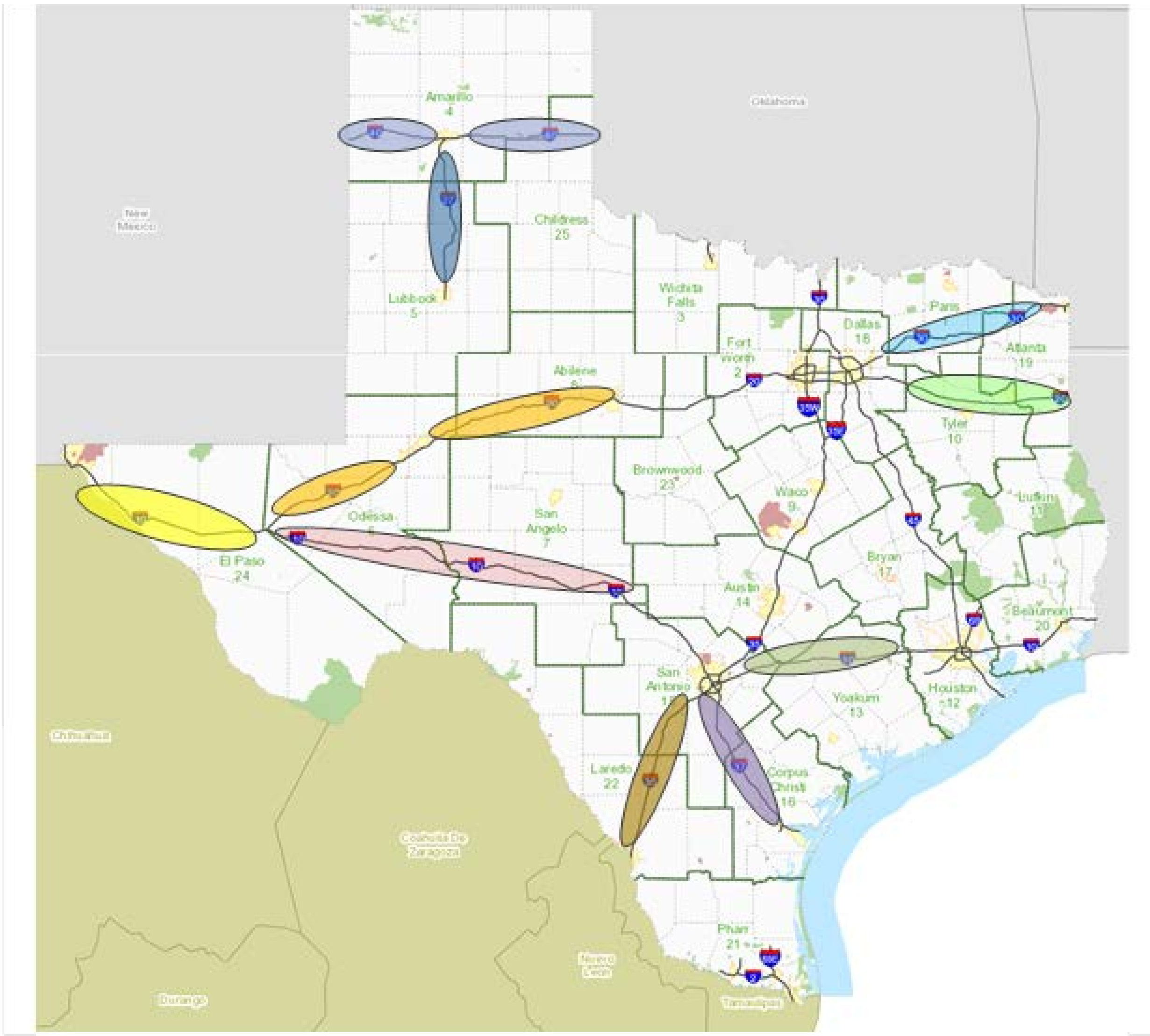


Figure 12. Locations of Candidate Corridors for Demonstrating Truck Platooning in Texas.

Geometric Features

Average Number of Exits and Entrances

Truck platoons are intended to operate over long distances with limited points where entering and/or exiting traffic would tend to impede vehicles staying on the mainline roadway. A larger number of exits would be less desirable for safe operations due to vehicle speed change and driver decision-making required at merge and diverge points.

Spacing between ramps should meet the requirements set forth in the TxDOT *Roadway Design Manual* (*89*) as follows:

- Entrance ramp followed by exit ramp: 2,000 ft (w/o aux. lanes), 1,500 ft (w/ aux. lanes).
- Exit ramp followed by exit ramp: 1,000 ft.
- Exit ramp followed by entrance ramp: governed by geometrics of the connections to the adjacent roadway or connecting roadway.

The research team counted the number of exits and entrances along the selected corridors for comparison purposes. For example, the I-10 segment from just east of El Paso to the I-10/I-20 split (141 miles) has 58 ramps (both entry and exit ramps) in both directions. The segment of I-10 from the I-10/I-20 split to just west of Fort Stockton (distance of 68 miles) has 26 ramps in each direction.

Left versus Right Exits/Entrances

Left exits are less desirable than right exits due to violation of driver expectancy; consequently, corridors with left exits are less desirable. The corridor segments studied do not have any left exits.

Number of Sharp Curves or Other Extreme Features

Sharp curves and other extreme features create safety concerns with respect to driver expectancy and vehicle maneuverability. Specifically, commercial trucks are particularly susceptible to rollover due to their high center-of-gravity, so corridors with unusual alignment issues are undesirable. Corridors with higher occurrences of such features will be ranked lower than those with gentler alignment.

The two segments on I-10 noted above have curve advisory warning signs posted, indicating potential horizontal alignment hazards. The eastbound segment of I-10 from El Paso to the split had two curve speed advisories whereas the westbound segment had three.

Lane Width

It is desirable to operate commercial vehicle platoons on lane widths of 12 ft or greater. Since all selected corridors are interstate roadways, lane widths are expected to be 12 ft. Lane widths less than 12 ft would be a deterrent to selection of a corridor. A summary of lane widths is presented later in this document.

Horizontal Alignment

The roadways on which truck platoons operate should exceed the minimum horizontal curvature values provided in the TxDOT *Roadway Design Manual* (*89*). Accordingly, the design speed for horizontal curves should be at least 60 mph and the alignment should provide the recommended decision sight distance.

Vertical Alignment

Vertical alignment can be a factor in operating large trucks at relatively constant speeds and maintaining adequate sight distance. From a sight distance perspective, relatively short vertical curves are undesirable. Most of the grades on interstate roadways in Texas are not extreme from the standpoint of either percent grade or length of grade. However, corridors with flatter vertical alignment are more desirable for operating large trucks since speed differentials between trucks and non-trucks will be less. Also, differences in power and loading characteristics (i.e., weight-to-power ratios) for trucks operating in platoons might become a bigger issue where steeper and/or longer grades exist. The maximum desired grade would be 3.0 percent. According to the TxDOT *Roadway Design Manual* (*89*), the maximum length of grade at 3.0 percent to maintain no more than 10 mph speed reduction at 200 lb/hp is 1,700 ft.

Unfortunately, the research team was unable to find an adequate database to accurately assess the vertical alignment. Contacts with TxDOT's Transportation Planning and Programming Division revealed that the GeoHini database might have been useful but TxDOT does not maintain it and cannot vouch for its accuracy. In lieu of the more desirable data to quantify grade percent and lengths, the research team is using available public domain mapping to estimate grades that are steeper than normal. For example, the segment of I-10 east of El Paso to the split had one short segment of steep grade in each direction but its magnitude and length could not be established with the data available.

Shoulder Width

Shoulder widths (outside shoulders) for interstate roadways typically range from 8 ft to 12 ft with the higher end of the range being more desirable for truck platoons. This document provides a summary of shoulder widths later.

Infrastructure Quality

Pavement Type

Pavement type is either hot-mix asphalt or concrete with variations within each category (e.g., jointed concrete versus continuously reinforced concrete). Either pavement type is acceptable as long as pavement quality is in the acceptable range.

Pavement Quality

Pavement quality is important for platooning or non-platooning vehicles. For this analysis, the research team used two metrics to compare pavement quality across the candidate corridors. These two metrics are the condition score and the international roughness index (IRI). The condition score combines pavement distress and ride quality for each section of a corridor. As its name implies, the IRI is a measure of roughness along each wheel path and in each lane. TTI also requested the use of the skid number, which is a component of Pavement Management Information System (PMIS) database, with the caveat that these skid numbers would not be published or shared outside of TTI. However, TxDOT has not responded to this request.

The PMIS database is updated annually, with the most recent version of the database available for this project being the 2015 database. TTI extracted and summarized data from the PMIS database to compare average ride quality for each candidate section of roadway. The condition score, which combines several types of pavement distress and ride score, can have numeric values from 1 to 100 with the goal of the Commission of having on-system roadways at 70 or above. Table 20 summarizes the rating scheme for the condition score.

Table 20. Rating Scheme for Condition Score.

Condition Score	Numeric Range	Alpha Rating
Very Good	90 to 100	A
Good	70 to 90	B
Fair	50 to 70	C
Poor	35 to 50	D
Very Poor	1 to 35	F

The IRI measures the longitudinal profile of the roadway in each wheel path in units of inches (up and down) per mile of roadway length and can take on values ranging from 1 to 950. Low IRI values for a test section indicate that there is little up and down movement as a vehicle traverses the section and a driver would feel very little roughness. Another value extracted from the PMIS database is the outside (right) shoulder width. Desirable widths are 10 ft or greater. Based on data from the PMIS database, Table 21 summarizes the condition score, the IRI, and the right shoulder width. Each cell contains the percentage of that corridor's length that meets the specified criteria. For example, Figure 13 plots the condition score for the I-30 corridor indicating a very good condition score from mile marker (MM) 99 to MM 112 then dropping to a poor score from MM 112 to 121. Sixty-one percent of this corridor has a condition score of greater than 80 but 38 percent is less than 50.

Table 21. Percent of Freeway Segments with Different Pavement and Roadway Conditions.

Roadway	MM	Condition Score			International Roughness Index (in/mile)			Right Shoulder Width (feet)		
		C≤50	50< C≤80	C>80	IRI≤50	50< IRI≤100	IRI > 100	W<=10	10<W≤ 12	W>12
I-10	45–186	4%	6%	90%	5%	76%	19%	100%		
I-10	188–256			100%			100%	100%		
I-10	262–400		8%	92%	12%	81%	7%	91%	9%	9%
I-10	401–505		11%	89%	18%	82%		100%		
I-10	592–603			100%	25%	75%		100%		
I-10	616–716		8%	92%	29%	69%	2%	100%		
I-20	1–104			100%			100%	100%		
I-20	146–276		10%	90%	25%	71%	4%	96%	4%	4%
I-20	504–630	2%	9%	89%	19%	77%	4%	100%		
I-27	106–55	7%	11%	82%		87%	13%	100%		
I-27	45–16	10%	7%	83%		83%	17%	100%		
I-30	99–121	38%	1%	61%	12%	52%	36%	100%		
I-30	128–160			100%	28%	71%	1%	100%		
I-30	164–200			100%			100%	100%		
I-35	15–98		13%	87%	25%	73%	2%	100%		
I-35	102–148	2%	4%	94%	5%	91%	4%	100%		
I-37	18–127	3%	11%	86%	12%	81%	7%	45%		
I-40	0–60	2%	15%	83%	5%	85%	10%	100%		
I-40	86–176	7%	11%	82%	1%	73%	26%	100%		

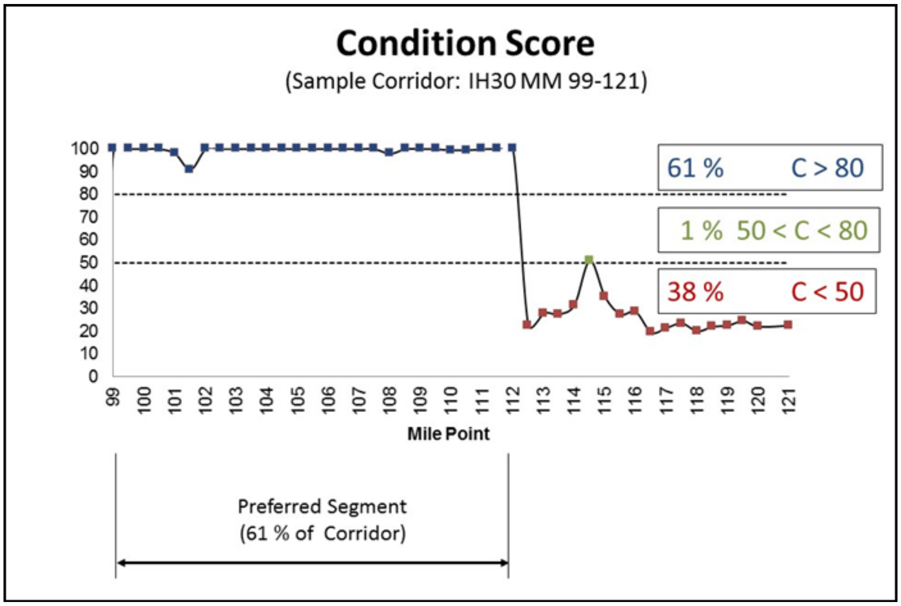


Figure 13. Use of Condition Score on I-30 Corridor.

Bridge Quality

Although bridges should not typically drive the decision-making process for ranking corridors, decision makers should not overlook this critical component. If some of the corridors were on non-interstate facilities, the process would typically avoid the weaker bridges. Since all routes are on interstates, bridges should be adequate.

Typical bridge design for purposes of this analysis would not necessarily restrict where truck platoons might operate but it might be a factor in the allowable minimum following distance. In general, individual truck axle and gross weights must abide by the limits set forth by the USDOT Federal Bridge Formula. This formula is designed to protect bridges by separating the loads applied by individual axles and axle groups to manage the bending moment in bridge components as the truck passes over the bridge. Each axle or axle group is allowed greater load the farther it is from the nearest axle or group up to a prescribed maximum amount. For example, the maximum allowable weight for a single axle with dual tires is 20,000 lb, and the maximum allowable weight for a standard tandem axle is 34,000 lb, other factors equal. Keeping the axles separated by some distance protects especially short-span bridges.

Applying this same principle to truck platoons requires that following trucks either be forced to maintain a minimum following distance (in accordance with the Federal Bridge Formula) or be limited by axle loading. This minimum following distance is not likely to be a serious problem in forming platoons but it is certainly a consideration.

Freight Network Considerations

Figure 14 shows the 2015 Texas Freight Network, and Figure 15 shows the freight tonnage for the year 2010 (most recent year readily available). Since the freight network selected by TxDOT represents the most appropriate roadways for high-volume, high-speed freight, it should include the corridors for operation of truck platoons. A quick analysis indicates that all of the selected corridors are on the freight network. Therefore, selection or ranking of corridors is not affected by this criterion since all candidates would be affected equally.

As shown in Figure 15, both I-35 and I-45 are characterized as two of the corridors that have the highest tonnage of truck freight movement in 2010. Projections for the year 2040 indicate that the truck freeways carrying the highest tonnage will be:

- I-35.
- I-45.
- I-40 west of Amarillo.
- Segments of I-10.

Truck tonnage should be useful in selecting initial corridors, and especially when combined with average daily traffic and average daily truck traffic, it would be useful in the corridor selection process.

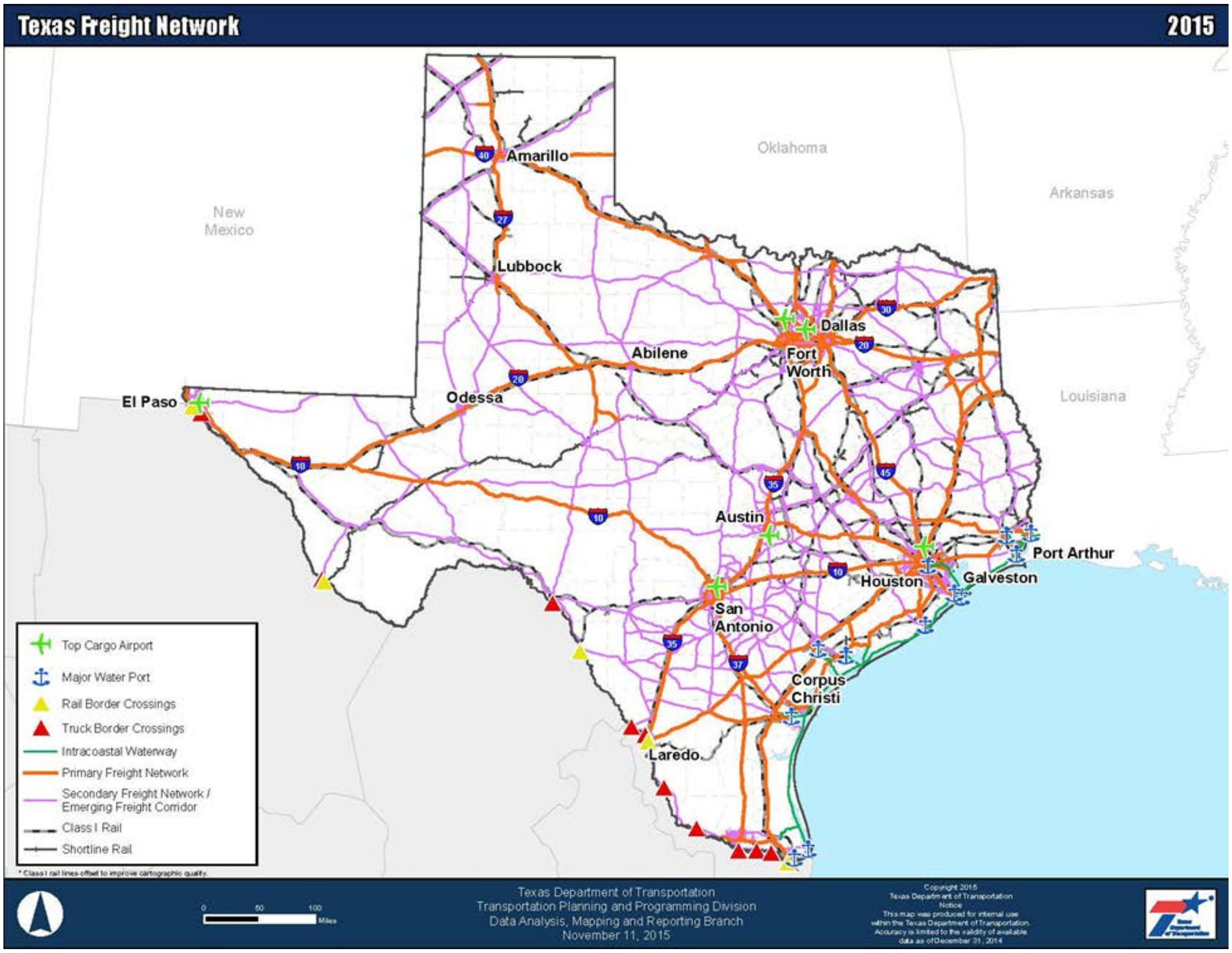


Figure 14. Texas Freight Network.

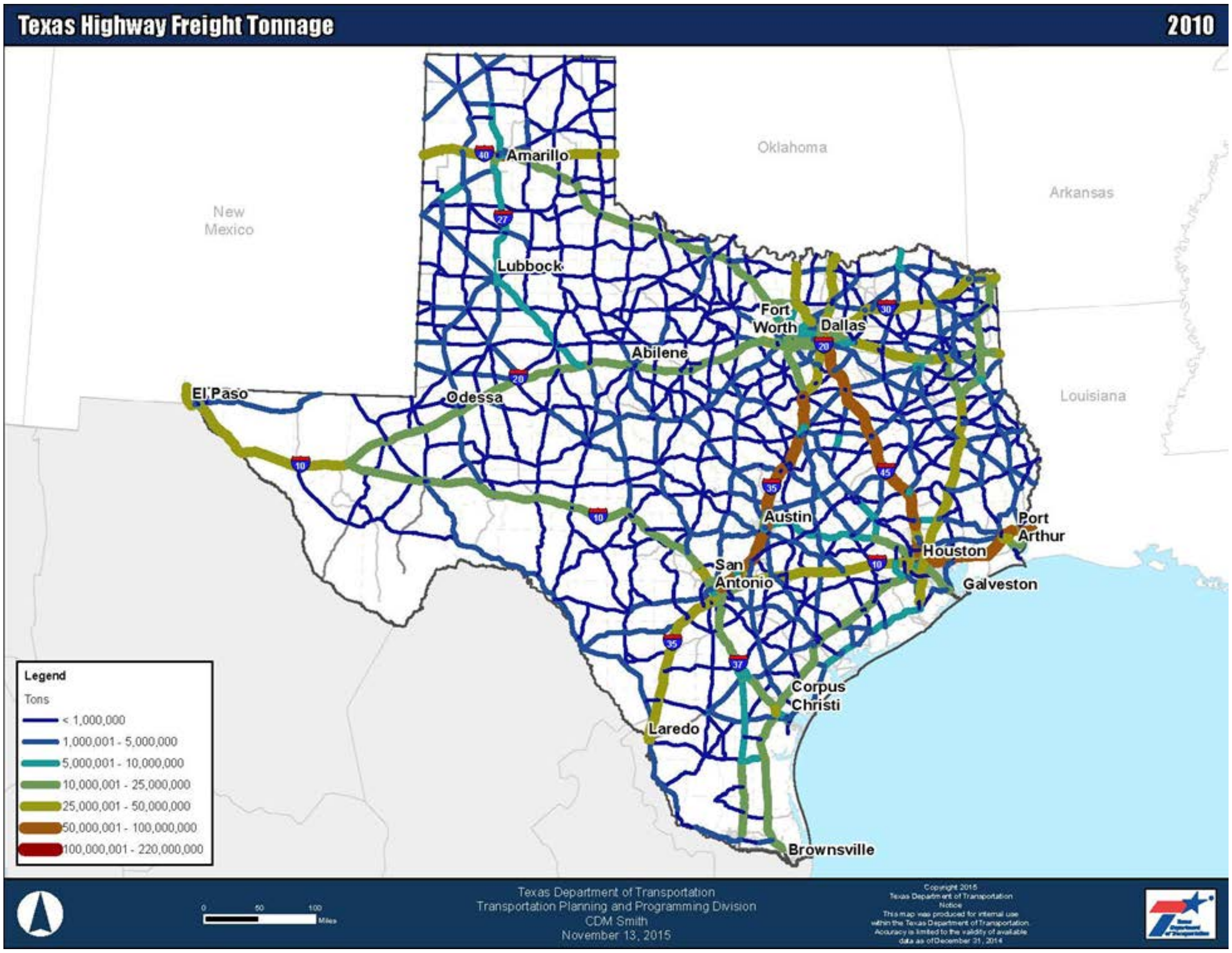


Figure 15. 2010 Texas Highway Freight Tonnage.

Truck Volume and Fleet Mix

The PMIS database provides ADT and truck percentage by roadway segment. As a general rule, the initial demonstration of truck platoons should occur on low- to moderate-volume roadways and in non-urban areas. The initial corridor selection limited corridors to rural interstate segments only, so that criterion is already met. As far as overall traffic volumes and truck volumes are concerned, the selection should favor lower volumes of vehicles overall to minimize potential vehicular conflict.

Potential Staging Areas

Staging areas are necessary for at least some scenarios of pairing trucks to operate in platoons. Perhaps the best locations for *ad hoc* pairing of trucks would be truck stops where departing trucks would have been serviced and refueled, and drivers have had a chance to eat a meal or at least to get outside the cab for the sake of alertness. Another staging area option might be rest stops that have sufficient space to park trucks. Table 22 indicates some potential staging areas that should be conducive to ad hoc platoon formation.

Table 22. Potential Staging Areas along Selected Corridors.

Roadway	Limits	Staging Opportunities [a]	
		EB or NB	WB or SB
IH0010	East of El Paso to I-10/I-20 Split	Ex 37, Flying J, Love's, Petro	Rest Area just w of I-10/I-20 split
IH0010	I-10/I-20 Split to West of Fort Stockton	Rest Area just w of I-10/I-20 split	Ex 259, Flying J
IH0010	East of Fort Stockton to Sonora	Ex 261, Love's	Ex 400, Town and Country
IH0010	Sonora to West of Kerrville	Ex 400, Town and Country	Rest Area MM 514 WB
IH0010	East of Schertz to West of Seguin	MM 590, Rest Area, Universal City, TX	Ex 604, Love's
IH0010	East Seguin to West of Sealy	Ex 615, Weigh Station	Ex 716, Sealy Truck Stop
IH0020	East of I-10/I-20 Split to Odessa	Rest Area just w of I-10/I-20 split	EX 121, Flying J (SW corner)
IH0020	East of Midland to West of Abilene	Ex 138, Flying J	Ex 278, Top-18
IH0020	East of Terrell to Louisiana Border	Ex 503, TA Terrell	Ex 635, Welcome Center, Waskom, TX
IH0027	South of Canyon to North of Plainview	Love's, Ex 116 at Hwy 335, Amarillo	N/A
IH0027	South of Plainview to North of New Deal	N/A	New Deal Travel Center, FM 5600 (maybe)
IH0030	East of Greenville to West of Sulphur Springs	Ex 94b, Valero Fuel Stop, Greenville	N/A
IH0030	East of Sulphur Springs to West of Mount Pleasant	N/A	N/A
IH0030	East of Mount Pleasant to West of New Boston	N/A	Ex 201, Hwy 8, Total Fuel Stop (Valero)
IH0035	North of Laredo to South of Pearsall	Flying J, Laredo, Ex 13	Petro, Ex 101 Pearsall
IH0035	North of Pearsall to South of San Antonio	Petro, Ex 101 Pearsall	Love's Ex 144 I-35
IH0037	North of Corpus Christi to South of San Antonio	CC Truck Stop, Ex 3a I-37	SA: Pilot Travel Ctr, Ex125, I-37
IH0040	New Mexico Border to West of Amarillo	Comm ctr 3mi west of NM border	Exit 74, Love's Travel Stop
IH0040	East of Amarillo to Oklahoma Border	Ex 74/75 Love's, Pilot, Petro Ex75	Enf pullout, 1 mi west of OK border

[a] Source of Truck Stop information: http://www.findfuelstops.com/truck-stop-in-tx (*91*).

Locations of Activity Centers

The research team requested locations of activity centers that might coincide with pre-selected corridors. One reason these activity centers are important for longer term formation and operation of truck platoons is that platoons can easily form on-site at these centers. Common origins and knowledge of destinations provides fertile ground for formation of platoons. Therefore, corridors with higher numbers of activity centers in close proximity would give them a higher ranking. Table 23, Table 24, and Table 25 summarize the locations of major activity centers around Texas sorted by retailers, manufacturers/distributors, or grocery, respectively. The next step was to locate these centers to determine their proximity with respect to the selected corridors. Activity centers located close to corridors will enhance the value of that corridor for truck platooning.

Table 26 shows other freight activity centers that also need to be considered. The types of centers include the following:

- Seaports.
- Airports/air cargo facilities.
- Rail yards/rail facilities.
- Border crossings.
- Oil and gas producing regions.
- Intercity rail corridor capacity needs.

Table 23. Selected Texas Distribution Centers over 500,000 Square Feet (Retailers).

Distribution Center[1]	Address	City	Size (sq. ft.)	TxDOT District
99 cents Only Stores (Ex-Albertsons)	23623 Colonial Parkway	Katy	741,000	HOU
Academy	1800 N. Mason Road	Katy	1,500,000	HOU
Blockbuster	3000 Redbud Blvd.	McKinney	818,000	DAL
Container Store	500 Freeport Parkway	Coppell	725,000	DAL
Dillards	4501 N. Beach Street	Fort Worth	716,000	FTW
Do-It-Best (u.c.)	801 Hewitt Avenue	Waco	500,000	WAC
Family Dollar	3101 E. I-20	Odessa	907,000	ODA
Home Depot (Ex-KMart)	2200 S. US Bus 45	Corsicana	1,453,000	DAL
Home Depot	6115 FM 1405	Baytown	755,000	HOU
Home Depot (u.c.)	8103 Fallbrook Drive	Houston	535,000	HOU
Home Interiors	1649 W. Frankford Rd.	Carrollton	659,000	DAL
JC Penney	1701 Intermodal Parkway	Haslet	1,200,000	FTW
Kohl's	1600 I-45	Corsicana	540,000	DAL
Lowe's	955 Lowe's Lane (I-30 W)	Mt. Vernon	1,100,000	PAR
Mervyn's (ex)	1600 Plano Parkway	Plano	533,000	DAL
Macy's (ex-Foley's)	2103 Ernestine	Houston	810,000	HOU
M.J. Designs/Michaels	500 Airline Drive	Coppell	504,000	DAL
Radio Shack[2]	900 Terminal Road	Fort Worth	1,142,000	FTW
Rooms to Go	3500 S. Watson Road	Arlington	851,000	FTW
Sears	2775 Miller Road	Garland	878,000	DAL
Stage Stores	506 Beall Blvd.	Jacksonville	500,000	TYL
Target	13786 Harvey Road	Tyler	1,630,000	TYL
Target	4333 Power Way	Midlothian	1,350,000	DAL
Toys R Us	3800 Railport Parkway	Midlothian	846,000	DAL
Tractor Supply (exp.	2801 Corporation Parkway	Woodway	654,000	WAC
True Value Hardware	2601 E. SH 31	Corsicana	775,000	DAL
Walgreens	710 FM 664 (Ovila Rd.)	Waxahachie	650,000	DAL
Wal-Mart #7042	4554 E. Greenwood St.	Baytown	2,000,000	HOU
Wal-Mart #6068	2120 N. Stemmons	Sanger	1,200,000	DAL
Wal-Mart #7036	3162 Brast Road	Sealy	1,100,000	YKM
Wal-Mart #6036	14868 FM 645	Palestine	1,000,000	TYL
Wal-Mart #6012	3100 N. Quincy Rd.	Plainview	1,000,000	LBB
Wal-Mart #6016	3900 N I-35	New Braunfels	980,000	SAT
Wal-Mart #7010	20131 Gene Campbell Road	New Caney	890,000	HOU
Wal-Mart #6083	9605 NW H.K. Dodge Loop	Temple	800,000	WAC
Wal-Mart #6056	591 Apache Trail	Terrell	750,000	DAL
Wal-Mart #6005	201 Old Elkhart Road	Palestine	660,000	TYL

[1] u.c. – under construction.

[2] Includes some manufacturing.

Table 24. Selected Texas Distribution Centers over 500,000 Square Feet (Manufacturers/Distributors).

Distribution Center[1]	Address	City	Size (sq. ft.)	TxDOT District
Army-Air Force	1801 Exchange Parkway	Waco	625,000	WAC
Bridgestone America	600 Gateway Parkway	Roanoke	608,000	DAL
Caterpillar (u.c.)	Exchange Parkway	Woodway	(750,000)	WAC
General Mills (u.c.)	4901 Henrietta Creek Road	Roanoke	670,000	DAL
Haggar Clothing Co.	5401 N. Riverside Drive	Ft. Worth	665,000	FTW
Igloo Products[2]	777 Igloo Road	Katy	1,400,000	HOU
LG Electronics	13700 Independence Pkwy	Haslet	500,000	FTW
Mattel	501 Meacham Road	Fort Worth	1,000,000	FTW
Michelin	8800 City Park Loop	Houston	663,000	HOU
Orgill (u.c.)	7001 Elder Lake Road	Kilgore	530,000	TYL
Nestle	13600 Independence Pkwy.	Haslet	525,000	FTW
Phillips Electronics	300 Freedom Drive	Roanoke	776,000	DAL
Solo Cups (ex-Circuit City)	3737 Duncanville Road	Duncanville	510,000	DAL
Whirlpool (ex-GM Parts)	1101 Everman Parkway	Fort Worth	852,000	FTW
Whirlpool	14900 Frye Road	Fort Worth	500,000	FTW

[1] u.c. – under construction.

[2] Includes some manufacturing.

Table 25. Selected Texas Distribution Centers over 500,000 Square Feet (Grocery).

Distribution Center[1]	Address	City	Size (sq. ft.)	TxDOT District
Albertsons	7550 Oak Grove Road	Fort Worth	1,030,000	FTW
Aldi (u.c.)	2500 Westcourt Road	Denton	500,000	DAL
Grocers Supply (e.g., Fleming, Safeway; not now DC)	2600 McCree Road	Garland	1,080,000	DAL
Grocers Supply	3131 E. Holcombe Blvd.	Houston	959,000	HOU
HEB	4710 N. IH-35	San Antonio	1,380,000	SAT
HEB	2301 Hunter Road	San Marcos	~650,000	AUS
Kraft	1006 Railhead Dr	Haslet	650,000	FTW
Kroger	701 Gellhorn Drive	Houston	880,000	HOU
McLane Southwest	2828 Industrial Blvd.	Temple	500,000	WAC
Randall's	10700 Telge Road	Houston	646,000	HOU
Randall's/Tom Thumb	743 Henrietta	Roanoke	1,260,000	DAL

[1] u.c. – under construction.

[2] Includes some manufacturing.

Table 26. List of Texas Locations Impacted by Increased Freight Activity.

Freight Facility	City/Region	Facility Type
Seaports		
Port of Beaumont	Beaumont	Port/Rail
Port of Brownsville	Brownsville	Port/Rail
Port of Corpus Christi	Corpus Christi	Port/Rail
	La Quinta Container Terminal (planned)	
Port of Freeport	Freeport	Port/Multimodal

Freight Facility	City/Region	Facility Type
Port of Galveston	Galveston	Port/Rail
Port of Harlingen	Harlingen	Port/Rail
Port of Houston	Houston	Port/Rail
	Bayport Container Terminal	
	Barbours Cut Container Terminal	
Port of Port Arthur	Port Arthur	Port/Rail/Intermodal
Port of Port Lavaca – Point Comfort	Calhoun County	Port/Rail
Port of Orange	Orange	Port
Port of Victoria	Victoria	Port/Container-on-Barge
Airports/Air Cargo Facilities		
Dallas Fort Worth International Airport	Dallas-Fort Worth	Airport/Air Cargo
Fort Worth Alliance Airport/AllianceTexas	Fort Worth	Cargo Airport and Global Logistics Hub
George Bush Houston Intercontinental Airport	Houston	Airport/Air Cargo
William P. Hobby Airport	Houston	Airport/Air Cargo
San Antonio International Airport	San Antonio	Airport/Air Cargo
Laredo International Airport	Laredo	Airport/Air Cargo
Austin-Bergstrom International Airport	Austin	Airport/Air Cargo
Rio Grande Valley International Airport	Harlingen	Airport/Air Cargo
El Paso International Airport	El Paso	Airport/Air Cargo
Lubbock International Airport	Lubbock	Airport/Air cargo
Brownsville/South Padre Island Int'l Airport	Brownsville	Airport/Air Cargo
Rail Yards/Rail Facilities		
BNSF Haslet Yard/ AllianceTexas	Fort Worth	Rail
Union Pacific (UP) Classification Yard Facility (planned)	Hearne/Mumford	Rail/Intermodal
UP Dallas Intermodal Terminal	Dallas County	Rail/Intermodal
Port San Antonio	San Antonio	Inland Port (Air Cargo/ Rail/Intermodal)
UP San Antonio Intermodal Terminal	San Antonio	Rail/Intermodal
Kansas City Southern Railway (KCS) Rosenberg Yard	Rosenberg	Rail
UP Santa Teresa Intermodal Facility	El Paso	Rail/Intermodal/Border Crossing
Border Crossings		
	Truck	Rail
El Paso, TX–Cd. Juárez, Chihuahua		
Eagle Pass, TX–Piedras Negras, Coahuila		
Laredo, TX–Nuevo Laredo, Tamaulipas		
Brownsville, TX–Matamoros, Tamaulipas		
Presidio, TX-Ojinaga, Chihuahua (rail crossing scheduled to reopen by 2016)		
Oil and gas Producing Regions		
	Truck	Rail
Midland		
Odessa		
San Angelo		
Bryan/ College Station		
Lubbock		
Amarillo		
LaSalle County/ Gardendale		
San Antonio		
NETEX/Haynesville Shale/ East Texas Region		
Granite Wash Region		

Freight Facility	City/Region	Facility Type
Intercity Rail Corridor Capacity Needs		
	Truck	Rail
South Texas Coast		
East Texas		
West Texas/La Entrada al Pacifico/ South Orient Corridor		
BNSF TransCon		
UP Sunset Line		
UP T&P Line		
UP Routes from Houston to (planned) Mumford Classification Yard		

Matrix Framework for Corridor Evaluation

The matrix framework for assessing the corridors or sites is a two-dimensional matrix with the list of sites (see Table 19) on one axis and the following values on the other:

- General considerations.
  - Rural interstate roadways.
  - Rehabilitation schedule.
  - Air quality rating.
- Geometric features.
  - Number of exits and entrances.
  - Number of left vs. right exits/entrances.
  - Number of sharp curves or other extreme features.
  - Lane width.
  - Shoulder width.
  - Horizontal alignment.
  - Vertical alignment.
- Infrastructure quality.
  - Pavement type.
  - Pavement quality.
    - Skid number.
    - IRI score.
    - Condition score.
  - Bridge quality.
- Freight network considerations.
  - Truck volume and fleet mix.
  - Potential staging areas.
  - Locations of activity centers.

The matrix framework could use a rating system used for other projects by team members to develop outcomes based on disparate ways of rating each metric. For example, pavement condition score is a quantitative measure of ride quality with specific thresholds for desirable or undesirable ratings. However, other values might be assigned qualitative thresholds such as good, better, and best. Qualitative and quantitative measures should be combined in a methodical manner, starting with consensus on the threshold values.

SUITABLE APPLICATIONS

The research team applied alternative concepts identified in previous efforts to the sites/corridors identified to determine which alternative concept best address the needs and situations of the corridor. Additionally, the task required the team to identify advantages and disadvantages, and risks associated with deployment scenario.

The research team noted that a preliminary assessment and down selecting of candidate corridors was based upon corridor characteristics that provide the safest and most effective environment to initially deploy commercial truck platooning in order to assess benefits. This led the research team to select to a rural corridor with similar geometric and traffic flow characteristics. Consequently, the research team concluded that the four alternatives defined previously would perform similarly on all of the corridors. The research team noted that a specific alternative should ultimately be selected and recommendation based upon an evolutionary deployment concept. At this time, the most reasonable alternatives for a safe, effective, and reliable introductory deployment are those using a Fleet Management Center or PSP. While the research team's final recommendation may change based upon research findings in later efforts, its initial recommendation is to initially deploy Alternative 4, Trip Platooning. Although the evolutionary timeline is unclear at this time, the subsequent steps of an evolutionary deployment then be Alternative 3, Scheduled Platooning, followed by Alternative 2, Guided On-the-Fly Platooning. Finally, if feasible to deploy the system without a Fleet Management Center or PSP, Alternative 1, Ad Hoc Platooning would be deployed. Chapter 3 details the advantages and disadvantages.

PRELIMINARY SIMULATIONS OF SCENARIOS

The research team used a simulation model and appropriate simulation control algorithms to analyze the impacts of deploying a truck platooning system in the selected corridors. The simulation model assessed the fuel consumption benefits associated with using truck platoons in the corridor and examined the effects of deploying a truck platooning systems on non-truck traffic in the corridor.

The research team completed the CACC algorithm development and implementation for the simulation using Vissim simulation software and a Vissim Application Program Interface. CACC is the foundation for the automated longitudinal control necessary for commercial truck platooning. Next the team developed a methodology for computing emissions and fuel savings using the Comprehensive Modal Emission Model (CMEM) (*92*) and the results from Vissim. The researchers then implemented a script for batch processing of Vissim trajectory files for air quality assessment and added a data logging feature in Vissim for collecting detailed vehicle records for operational performance measurement.

Figure 16 shows a snapshot of the simulation animation. The black vehicles are regular cars. The blue trucks are platoon-capable vehicles in a normal driving mode. The red and yellow trucks indicate a LV and a FV during a platooning operation.

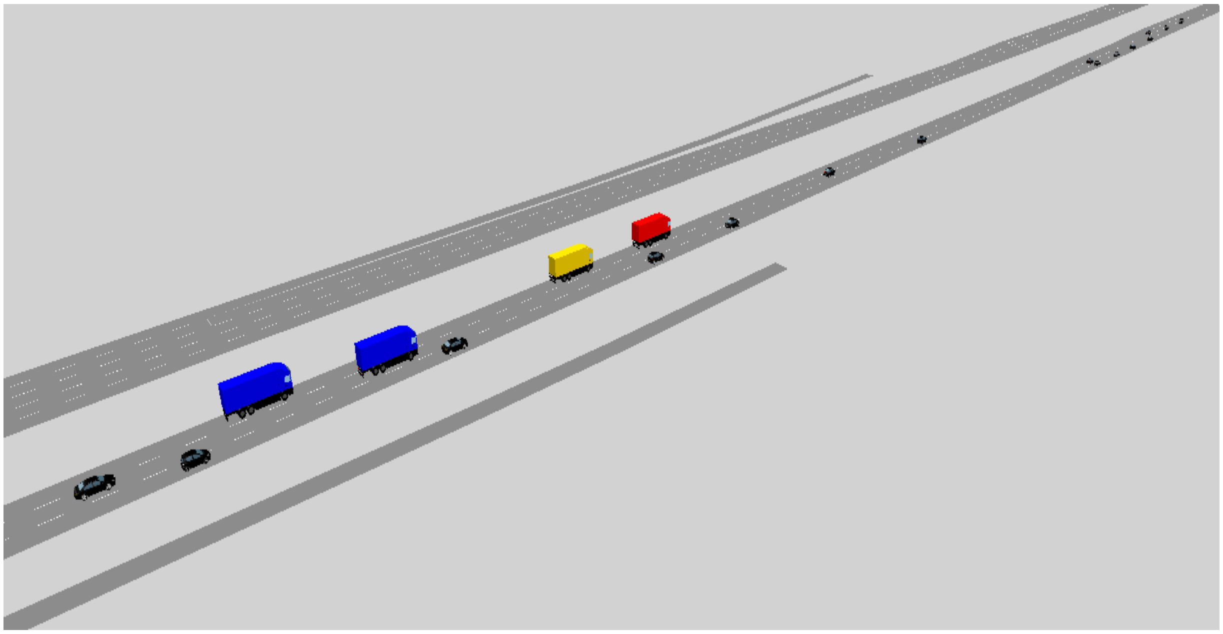


Figure 16. Preliminary Simulation Animation.

Figure 17 shows preliminary fuel consumption results, depicting the ratio of the fuel savings versus the percentage of time spent in automated platooning mode for a given set of variables (e.g., speed, following distance/gap, given geometric configuration for ramp spacing, AADT, and percentage of AADT that are trucks). The lower plot shows fuel savings for the LV and the upper plot shows fuel saving for the FV. The ratio (y-axis) is based on the fuel consumption of the same pair of trucks with and without platooning. For the base run, all platoon-capable trucks are tracked for fuel consumption with the platooning feature deactivated. Then, the platooning feature was activated for the second run, allowing a comparison between the two scenarios.

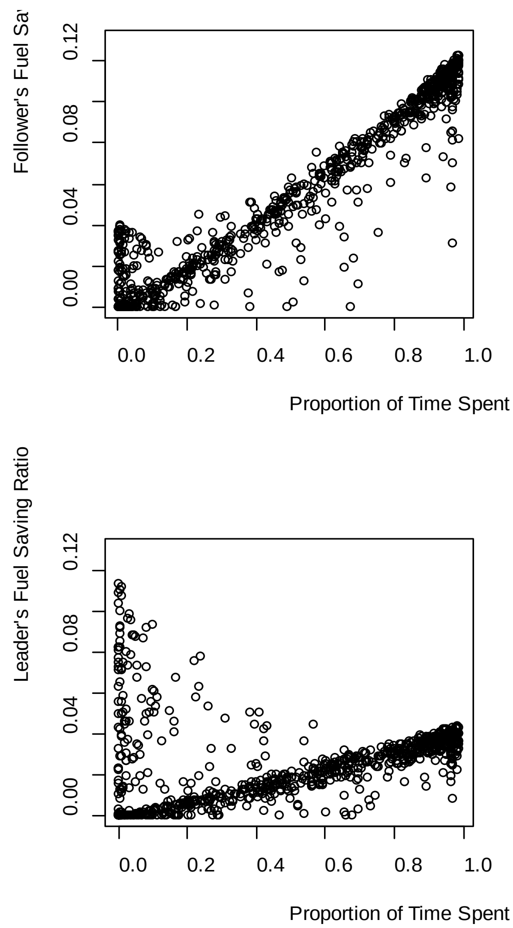


Figure 17. Preliminary Simulation Results.

From the graph, when in automated platooning mode 50 percent of the time, the LV will save about 2.5 percent, and the FV will save about 6 percent in fuel consumption.

COST/BENEFIT ANALYSES

This project developed and demonstrated two trucks in platooning in a closed environment. As part of this study, a simulation task quantified the environmental and operational impacts of multiple two-truck platooning in a normal traffic environment. Using microscopic traffic simulation, the truck platooning operation was modeled and evaluated in a controlled experiment under different operating assumptions.

Literature indicated that platooning has potential to increase freeway throughput and stability and decrease fuel consumption and emissions. The premise for fuel consumption from truck platooning is that vehicles with small spacing experience a reduction in wind drag. Past studies have analyzed the effect of close following on fuel consumption and emissions. Alam et al. (*93*) evaluated platoons formed by heavy vehicles equipped with ACC. They added a feature so as to allow the FV to obtain the information of traffic conditions ahead of the LV, which is similar to the CACC framework. The close following and reduction in wind drag resulted in a reduction in fuel consumption between 4.7 to 7.7 percent where smaller gaps yield higher fuel reduction. Bonnet et al. (*94*) used an electronic tow bar to allow two heavy vehicles to move at a close spacing. The LV was driven manually, and the FV had a controller to follow the LV automatically. They ran a series of experiments at different speed and spacing combinations with the highest spacing being 16 m. The authors found a reduction in fuel consumption at all the levels. The fuel saving increases with the decrease in clearance but it reaches a plateau at a 10 m spacing. A fuel saving was found to be in the range between 5 and 10 percent. Tsugawa et al. (*95*) conducted a study to evaluate platooning with respect to three CACC-equipped heavy vehicles. The study showed similar findings with a 2.1 percent reduction in CO_2 at a spacing of 10 m and a market penetration rate of 40 percent. All these studies indicated that closer spacing between platoon members results in lower fuel consumption and emissions. The spacing between close FVs is a key determinant in quantifying the magnitude of environmental benefits. It is desirable for fleet managers, policy makers, and trucking companies to understand how this technology performs under various traffic conditions and platooning characteristics.

Traditionally, microscopic simulation tools provide a cost effective, robust, and reliable method for analyzing the impacts of traffic operations. With the emerging CV/AV technology, these tools must be properly modified in order to be capable of modeling these new applications. For truck platooning, the simulation must be able to use different car following and lane changing models in order to properly replicate the platooning effects. In this study, researchers chose Vissim model due to our extensive experience with the tool and its capability to replace its existing driver model through the driver model application program interface. The driver model is defined by car following and lane changing models. Previous research provides different car following models that can be used for modeling platooning with some modifications. Intelligent driver model by Treiber et al. (*96*) can be modified for modeling ACC- and CACC-equipped vehicles. Vanderwerf et al.'s (*97*) car following model for an ACC and CACC system is a modified version of Godbole's driver model. The basic aim of subject vehicle in this model is to maintain a safe distance from the preceding vehicle. Van Arem et al. (*98*) developed a desired distance based model, while Shladover et al. (*99*) developed a simplified version of car following model, which maintains a constant time gap when the subject vehicle is following other vehicles during CACC operation. In addition, to improve comfort for CACC systems, a majority of driver models put conservative upper and lower bounds on acceleration. In this study, researchers modified the Shladover et al.'s car following model for longitudinal control and then added lane change logic for lateral control during platooning operation.

Model Development

This study considers only two-truck platooning in the first phase of the study. In this way, the vehicles in the platoon can either be a leader or a follower. This also simplifies the modeling of lane change control for the follower as only one vehicle needs to change the lane with the leader.

Car-Following Model

The CACC model used in this paper is based on Shladover et al.'s study (*99*). The ACC and CACC controllers use the same model but employ different gap settings. Each controller has two modes, speed regulation and gap control modes. In speed control, the acceleration is determined based on difference of the ego vehicle speed and its CACC set desired speed:

$$v_e = v - v_d \quad \text{(Equation 1)}$$

$$\boldsymbol{a_{sc} = bound\ (-0.4 \cdot v_e, 2, -2)} \quad \text{(Equation 2)}$$

$$\boldsymbol{a = a_{sc}} \quad \text{(Equation 3)}$$

In gap control, the acceleration of ego CV is decided based on difference of the ego vehicle following spacing and the desired spacing:

$$v_e = v - v_d$$

$$a_{sc} = bound\ (-0.4 \cdot v_e, 2, -2)$$

$$\boldsymbol{s_d = T_d \cdot v} \quad \text{(Equation 4)}$$

$$\boldsymbol{s_e = s - s_d} \quad \text{(Equation 5)}$$

$$\boldsymbol{a = bound\ (s + 0.25 \cdot s_e, a_{sc}, -2)} \quad \text{(Equation 6)}$$

where,

v = speed of controlled CC-CACC vehicle (m/s).

v_d = desired speed set by driver or roadway speed limit (m/s).

v_e = speed error (m/s).

a_{ac} = acceleration by speed control (m/s^2).

s = spacing between ego CV and its leading vehicle (m).

s_d = desired spacing (m).

s_e = spacing error (m).

T_d = desired time gap (s).

$\text{bound}\left(x, x_{ub}, x_{lb}\right)$ = $\max(\min(x, x_{ub}), x_{lb})$.

x_{ub}= upper bound value.

x_{lb}= lower bound value.

In speed control mode, the goal of ACC-CACC control is to reach the desired speed within 2.5 seconds. In gap control mode, the acceleration cannot exceed the speed control acceleration a_{sc}. This logic can keep vehicles from running over each other in simulations.

Lane Changing Model

The lane change decision in the simulation model is usually determined by the simulation's existing driver model. If the vehicles are allowed to make lane changes as they normally would under normal driving scenarios, the platoons would be frequently dissolved resulting in unrealistic platooning operation. To address this issue, researchers implemented an alternative lane change model for the FV when they are in the platooning mode. During the platooning, the LV would continue to drive in a normal human driving mode but the FV will receive the information about the impending lane change and the target lane as soon as the LV decides to change the lane. Then, upon receiving the information about impending lane change, the FV will perform a check on the available gap on the target lane. If the gap available on the target lane meets the specified threshold, the FV will simultaneously perform the lane change maneuver along the LV such that both vehicles can continue in platooning mode.

Emissions and Fuel Consumption

Commonly used tools such as Motor Vehicle Emission Simulator, CMEM, and VT-Micro can all be used to estimate various vehicular pollutants. These tools require second-by-second vehicle trajectory data for estimating emissions from individual vehicles. During platooning, there is an effect of wind drag reduction from close following distance, so the following distances must also be recorded along with the trajectory data for the adjustment.

In this study, CMEM is used to estimate emissions and fuel consumption from the trajectory data. Researchers developed an R script to process individual trajectories with CMEM executable module. Then, the second-by-second results were adjusted for reduced wind drags based on the following distances during platooning.

The wind drag reduction is based on the study by Hong et al. (*100*). Table 27 shows wind drag reduction ratios at different car spacing for the LV and FV in platooning. The FV benefits directly from less wind drag resistance while the LV's reduction is attributed to improved aerodynamics. The study also indicated that there are further reductions for both the LV and the FV up to around two car lengths albeit at different rates. Therefore, the values from the table were linearly extrapolated to get the wind drag reduction ratios for the distance between one and two car lengths. Other intermediate values for wind drag reductions were estimated by linear interpolation.

Table 27. Wind Drag Reduction Ratio for Platooning Vehicles (*100*).

Car Spacing (Car Length)	LV's $C_D/C_{Neutral}$	FV's $C_D/C_{Neutral}$
0.2344	0.6380	0.7278
0.2865	0.5910	0.6657
0.3802	0.6111	0.6978
0.5521	0.7848	0.6259
0.7448	0.8808	0.6724
1	0.9541	0.7379

Simulation Experiment

The simulation test bed is a three-lane 26-mile freeway section modified from the I-30 eastbound corridor between Fort Worth and Dallas, TX. All the ramp traffic volumes were turned off to provide a controlled environment for this experiment. The total simulation period was 135 minutes. The traffic volume profile used in the experiment began with low volume of 1000 vehicles per hour (vph) for 45 minutes and then increased to peak volume (two levels used, 3000 vph and 10000 vph) for 15 minutes and then reduces to 1000 vph for the rest of the simulation to ensure that all the vehicles inserted into the network have completed the trips for valid performance measurement. The first 30 minutes of the simulation were set aside for the warm-up period. The individual vehicle trajectories were logged for all CVs within the simulation. Because a volume profile of two levels was used in the simulation, each run generates a series of vehicles associated with two different volume levels. The correct volume levels associated each individual trajectory are identified by the vehicle's network entry time.

To simplify the vehicle types, all the regular vehicles are assumed to be passenger cars and all the CVs are trucks equipped with platooning capability. In this way, the market penetration rates also imply the percent of trucks in the network.

Data collection points were placed at the middle of the study freeway segment on every lane to collect cross-sectional speed and volume data. Travel time was recorded when each vehicle left the network.

All the ramp traffic was set to zero in order to provide a controlled environment for quantifying direct impacts of platooning. The test section can be considered as a basic freeway section. The speed limits were set at 65 mph and 70 mph for heavy-duty and light-duty vehicles, respectively.

The platoon forms using ad hoc formation strategy. This opportunistic formation requires two equipped trucks to follow each other continuously for a preset amount of time. This time duration allows for the process of communicating between the drivers and initiating the platooning process. The values of 10 and 20 seconds are used for this experiment. Once the minimum formation time is met, the platooning will form and the FV will tighten the following gap using the desired gap settings. The desired gap values of 0.6 and 1.1 seconds were selected based on Nowakowski et al.'s study on recruited drivers' choices of CACC settings on prototype vehicles in the field test (*101*). The gap tightening mechanism follows the car-following model described in the previous section. The platoon can be dissolved if there is a vehicle cut-in or a LV changes a lane and a FV is unable to change to the same lane due to inadequate gaps. Once the platoons break up, they can be formed again using the same ad hoc formation and the minimum following time criterion.

Simulation Runs

In summary, experimental factors considered are traffic conditions and platooning characteristics that are likely to influence fuel consumption and emissions. The following levels were used in the simulation setup:

- Traffic volume profile – 3000 vph and 10000 vph for peak volumes (1000 vph is used for off peak volume).
- Market penetration rate – 10 percent, 30 percent, 50 percent, and 70 percent.
- Desired following gap – 0.6 and 1.1 s.
- Minimum time required for formation – 10 and 20 s.

The factorial combination of all four factors produced a total of 32 scenarios for the simulation runs. In addition, to provide base scenarios for comparison, researchers ran simulations where platooning was deactivated to provide base case scenarios. There are a total of eight base case scenarios from a combination of two volume profiles and four market penetration levels as in the case where the platooning is activated. Each simulation scenario is run with the same seed number so that each individual vehicle from the base and the platooning cases with the same volume and market penetration rate can be paired for direct comparison and measurement of platooning effect on emission and fuel consumption.

Simulation Outputs

For each simulation scenario, simulation outputs consist of the following datasets:

- Connected truck trajectory files. This file logs second-by-second trajectory data along with following distances for all platoon-capable vehicles. This dataset is subsequently used in the CMEM for estimating emissions and fuel consumption. Other attributes logged for each equipped vehicle include platooning states and position in the platoon, which can be converted into percent of time spent in regular mode and platooning mode (separately as a follower and a leader). The travel time, travel distance, mean speed, and standard deviation of travel speed are also collected.
- Data collection point files. This feature is used to collect the cross sectional data of the test bed at 5-minute intervals. The data logs represent those typically collected via lane-

based fixed-point sensors, which are traffic volumes, speeds, and vehicle lengths. The data logs during the simulation warm-up period are excluded from the analysis.

- Vehicle trace file. This data log contains the second-by-second trajectory of all vehicles (equipped and non-equipped) in the network.

For each scenario, the dataset for each vehicle ID from the platooning case was matched with the same vehicle ID from the base case. In this way, the difference in emissions and fuel consumption for the same vehicle with and without platooning can be estimated. Further, the results are used to develop a model for predicting changes in fuel consumption. The calibrated model is described in the later section of this document.

Simulation Results

The analysis of platooning simulation results focuses on two performance measures, changes in fuel consumption and vehicle throughput. Figure 18 shows the box-and-whisker plots of average ratios of fuel savings for platooning vehicles matched with the base case (non-platooning) for all scenarios. Positive ratios indicate a reduction in fuel consumption and negative ratios imply vice versa. To interpret the box plots, the bottom and the top of the box represent the first and the third quartiles of the range while the black dot inside the box is the median value. This enables a quick way to visually examine the skewness of the dataset. The whiskers represent the 1.5*IQR (where IQR is the interquartile range) or the minimum and maximum of all of the data, whichever is smaller.

Table 28 summarizes mean and standard deviation of fuel saving ratios by simulation scenarios. Average fuel savings were found to be in the range of 0 to 12 percent depending on several factors as follows:

- High market penetration and higher volume generally result in more fuel savings except when the demand begins to exceed the capacity. In those cases, there is a negative effect in fuel savings that is likely attributed to stop-and-go traffic conditions.
- Higher variations in fuel saving ratios were observed in the case of high volume scenario. This could also be attributed to stop-and-go traffic conditions.

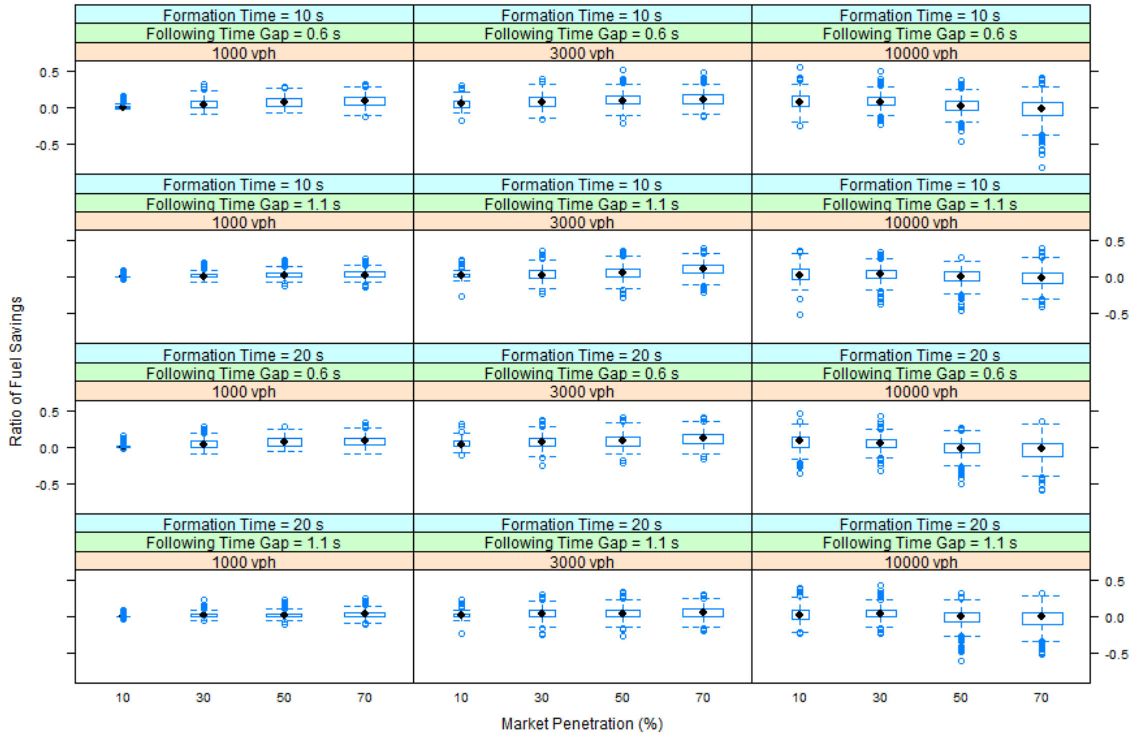


Figure 18. Effects of Platooning on Fuel Savings.

Figure 19 and Figure 20 show the relationship between percent of fuel savings as a function of percent time spent in platoon as a follower and a leader, respectively. These two figures show the range of effects on each individual truck. As expected, the savings are generally higher for the FV than the LV in the platoons. Only the vehicles that are operating exclusively either in the FV or LV mode are included in the plots. The number of data points is higher in the case of 1000 vph because they are taken from the off-peak volume period, which exist in all simulation runs prior to the peak volume period.

Table 28. Fuel Saving Ratio Statistics by Scenarios.

Volume (vph)	MPR (%)	Follow Gap (s)	Formation Time (s)	Sample Size (vehicle)	Fuel Saving Ratio Mean	Fuel Saving Ratio SD
1000	10	0.6	10	112	0.021	0.041
1000	10	0.6	20	110	0.015	0.035
1000	10	1.1	10	112	0.006	0.021
1000	10	1.1	20	110	0.004	0.020
1000	30	0.6	10	412	0.057	0.073
1000	30	0.6	20	402	0.048	0.063
1000	30	1.1	10	410	0.027	0.046
1000	30	1.1	20	406	0.023	0.039
1000	50	0.6	10	716	0.081	0.072
1000	50	0.6	20	710	0.071	0.065
1000	50	1.1	10	721	0.036	0.053
1000	50	1.1	20	715	0.030	0.047
1000	70	0.6	10	988	0.094	0.078
1000	70	0.6	20	996	0.083	0.070
1000	70	1.1	10	992	0.042	0.058
1000	70	1.1	20	988	0.037	0.054
3000	10	0.6	10	77	0.056	0.079
3000	10	0.6	20	77	0.050	0.070
3000	10	1.1	10	76	0.025	0.061
3000	10	1.1	20	77	0.018	0.057
3000	30	0.6	10	226	0.087	0.099
3000	30	0.6	20	226	0.077	0.091
3000	30	1.1	10	227	0.041	0.088
3000	30	1.1	20	228	0.040	0.087
3000	50	0.6	10	370	0.111	0.102
3000	50	0.6	20	369	0.085	0.094
3000	50	1.1	10	370	0.064	0.095
3000	50	1.1	20	370	0.045	0.083
3000	70	0.6	10	533	0.121	0.091
3000	70	0.6	20	530	0.115	0.091
3000	70	1.1	10	530	0.109	0.090
3000	70	1.1	20	533	0.057	0.077
10000	10	0.6	10	159	0.090	0.117
10000	10	0.6	20	159	0.072	0.126
10000	10	1.1	10	157	0.042	0.124
10000	10	1.1	20	159	0.031	0.110
10000	30	0.6	10	383	0.088	0.088
10000	30	0.6	20	439	0.049	0.093
10000	30	1.1	10	435	0.043	0.094
10000	30	1.1	20	438	0.047	0.087
10000	50	0.6	10	523	0.023	0.100
10000	50	0.6	20	643	-0.026	0.110
10000	50	1.1	10	644	0.001	0.101
10000	50	1.1	20	645	-0.016	0.111
10000	70	0.6	10	828	-0.032	0.149
10000	70	0.6	20	825	-0.041	0.146
10000	70	1.1	10	825	-0.013	0.117
10000	70	1.1	20	819	-0.027	0.126

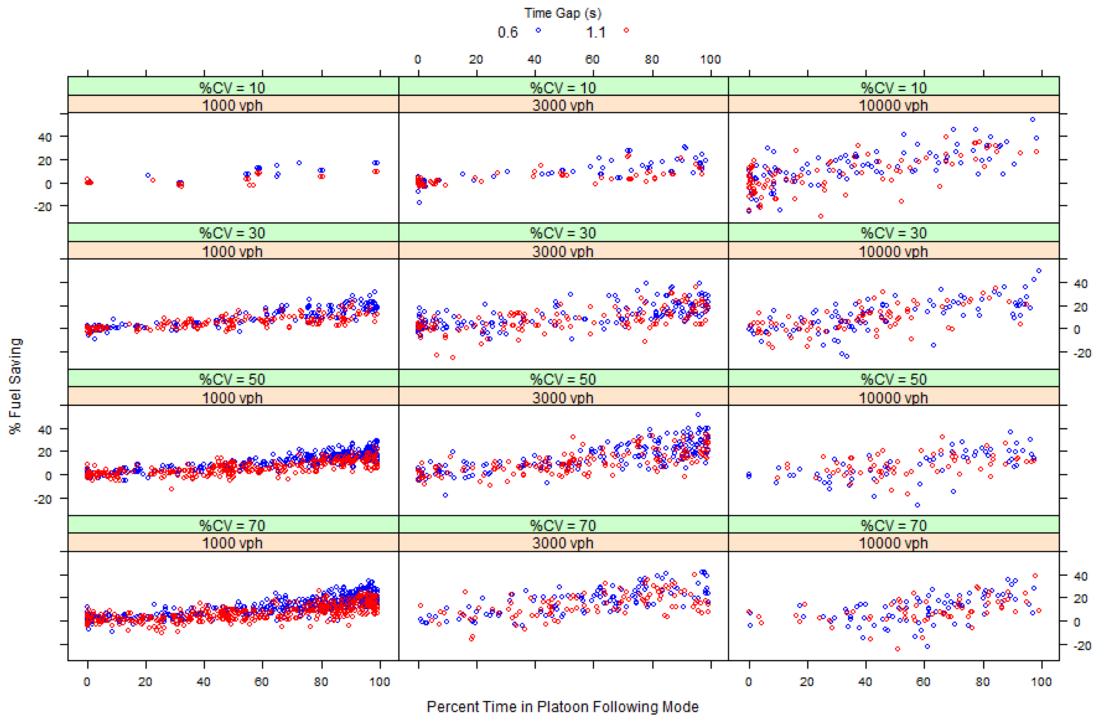


Figure 19. Relationship between Fuel Savings and Time Spent as FV.

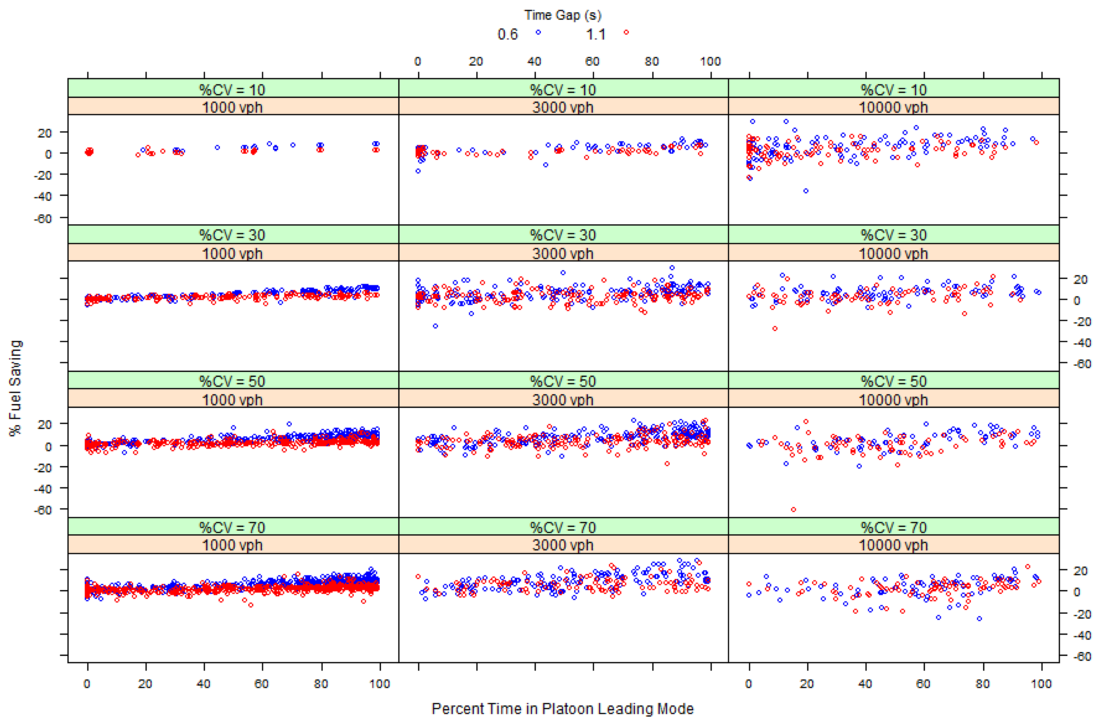


Figure 20. Relationship between Fuel Savings and Time Spent as LV.

The upper ranges of individual fuel savings were observed at about 40 percent and 20 percent for a platoon FV and LV, respectively. The tighter following gap (0.6 s) produces higher savings on average. There is a noticeable dispersion of saving range in the high volume conditions, which is similar to the pattern observed in the box plots.

Effects on Vehicle Throughput

The platooning is known to increase freeway throughput since tight and stable following gaps can be maintained via wireless connectivity. The cumulative vehicle throughput over time measures a number of vehicles that can pass through a cross section for a given scenario. In this case, the peak volume of 3000 vph did not show any pronounced increase in vehicle throughput regardless of market penetration because the traffic volume did not exceed normal freeway capacity. However, there is a pronounced increase in vehicle throughput over time for the peak volume of 10,000 vph. This confirms that freeway capacity can be increased with platooning technology without any infrastructure expansion even with two-vehicle platooning.

Figure 21 shows the increase in cumulative vehicle throughput over time when compared the platooning scenarios with the corresponding base cases. The label in the plot represents a combination of platooning status (on/off), desired gap setting (seconds), and minimum time required for platoon formation (seconds).

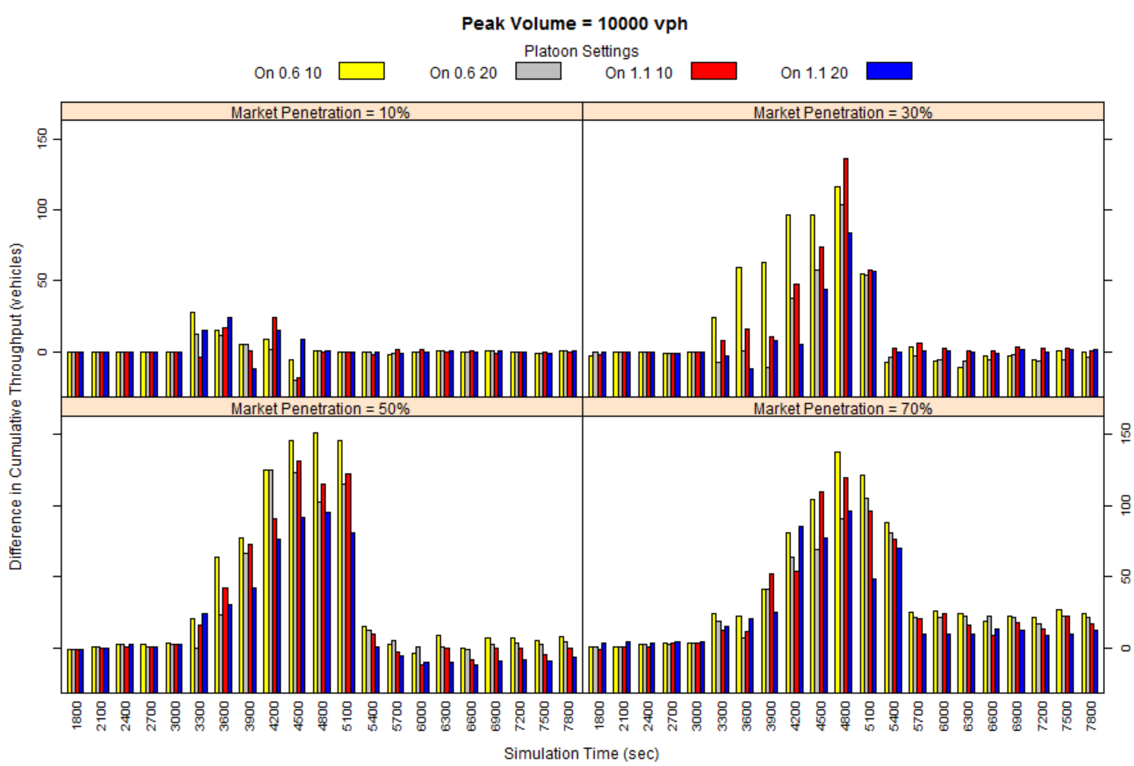


Figure 21. Differences in Cumulative Vehicle Throughput.

The increases are consistent when the market penetration is over 30 percent. The throughput increase benefits remain regardless of market penetration rates under high volume scenario but the fuel consumption benefits for individual platooning vehicles no longer exist under the same volume condition when the market penetration rates exceed 50 percent. This is likely because the traffic flow becomes unstable under high mix of platooning trucks, which led to conditions where platoon leaders are mostly governed by stop-and-go traffic conditions.

Model for Estimating Fuel Consumption

Assumptions

In order to provide more insight into platooning effects on fuel consumption, researchers used the simulation outputs to develop a regression model to estimate the percent changes in fuel consumption. The model developed is limited to the following conditions:

- The model was based on multiple two-truck platoons.
- The simulation outputs used in the calibration were based on a long trip length (approximately 26 miles). The model should be applicable for longer distance trips. However, there is a caveat for shorter trips since the incremental fuel consumption attributed to acceleration required to form platoons may not justify the potential fuel savings from wind drag reduction for short trips.
- The model assumes ideal wireless communication during platooning.

Estimated Model

To describe the model, first define the derived variables used in the model. The first one is the probability of platoon formation, which is defined as:

$$P_p = P_r(H < h_{max})^{0.1t_{min}} \times \frac{MPR}{100}; H\ exp(\lambda) \quad \text{(Equation 7)}$$

where

P_p = Probability of platoon formation assuming the time headway H follows exponential distribution with parameter λ.

$P_r(H<h_{\max})$ = Probability of time headway will be less than maximum time headway for platoon formation = $1-e^{-\lambda h_{\max}}$. For instance, the simulation run was using 100 meters as a threshold. Therefore, at 65 mph, the value of $h_{\max}$ is equivalent to 3.4 seconds.

$$\lambda = \text{arrival rate } (veh/second) = \frac{Volume\ (vph)}{Number\ of\ Lanes\ \times 3600}$$

t_{min} = minimum following time required to form a platoon (s).

MPR = Market penetration rate of platoon-capable trucks (%).

Note that the multiplier of 0.1 for t_{min} is an empirical adjustment to account for potential changes in headway when it takes longer to form the platoon.

The traffic condition also significantly fuel efficiency during platooning. This is represented in the model as the travel time buffer (%):

$$P_t = max\left\{0, \left(\frac{Travel\ Time}{Free\text{−}Flow\ Travel\ Time} - 1\right) \times 100\right\} \quad \text{(Equation 8)}$$

The travel time buffer indicates the extra amount of time in percentage that the traveler needs to spend in the traffic. The higher value means more congested traffic condition.

The percentages of time spent in platooning mode of the total trip time also determine fuel savings amount. The model considers the percent time spent as a leader (P_ℓ) and the percent time spent as a FV (P_f) as two separate variables. In addition, the following distance ratio (R_f) is also a significant determinant for fuel efficiency, which is defined as:

$$\boldsymbol{R_f = \frac{P_f}{S_f}} \quad \text{(Equation 9)}$$

where

P_f = Percent time spent as a FV.

S_f = Average following distance (ft).

The R_f value captures the effects of close following distance on fuel savings.

Finally, the calibrated model for estimating percent change in fuel consumption from platooning is described as:

$$\boldsymbol{F = 1.092 + 4.354P_p + 0.093P_l + 0.074P_f - 0.472P_t + 8.345R_f} \quad \text{(Equation 10)}$$

where

F = the percent change in fuel consumption with respect to base condition (no platooning).

P_p = the probability of platoon formation defined in Eq.

P_l = the percent time spent in platoon as a LV.

P_f = the percent time spent in platoon as a FV.

P_t = the percent travel time buffer defined in Eq.

R_f = the following distance ratio defined in Eq.

All the variables used in the model is significant at $\alpha = 0.05$. The model's goodness of fit using adjusted R-square value is 0.40.

Example of Model Use in Economic Analysis

Assume that a fleet operator would like to equip a two-truck platooning system at a cost of $10,000. The analyst would like to determine how long it would take to recoup the initial cost of the equipment.

Determine the following parameters for the analysis:

- Traffic volume = 5000 vph.
- Number of lanes = 3.
- Market penetration = 10 percent.
- LV: Leading mode = 40 percent, Following mode = 0 percent, Non-platoon mode = 10 percent.
- FV: Following mode = 40 percent, Leading mode = 0 percent, Non-platoon mode = 10 percent.
- Average following distance = 50 ft.
- Average travel speed = 60 mph.
- Average free-flow speed = 65 mph.
- Maximum distance for platoon formation = 300 ft.
- Minimum following time for formation = 10 seconds.

Using the prediction model described in the previous section, researchers can estimate the following:

- Fuel savings for the leader in a platoon = 7.16 percent.
- Fuel savings for the follower in a platoon = 1.25 percent.

If the average fuel efficiency without platooning is 6 miles/gallon or 0.167 gallon/mile, that means on average a pair of platoon will save about $0.167\times(0.0716+0.0125) = 0.014$ gallon/mile. Assume the diesel price of $2.50/gallon, it will take approximately $10000/(0.014\times2.5) = 285{,}714$ miles to recover the capital cost.

CONCLUSIONS

The researchers conducted a truck platooning simulation for two-truck platoons in a mixed traffic condition using Vissim microscopic simulation. The fuel consumption and emissions were estimated using CMEM. The second-by-second results from CMEM were adjusted using the reduced wind drag coefficients based on second-by-second following distances.

Platooning can reduce fuel consumption up to 12 percent on average. From individual trucks' viewpoint, the upper ranges of savings were observed at 40 percent for the follower and 20 percent for the leader in a platoon. The ideal conditions were moderate traffic volume and high MPR. The fuel consumption performance reduces greatly in a congested traffic condition, which is likely attributed to stop-and-go traffic governing the flow of the platoons.

The throughput increase was observed under high volume condition when the MPR is greater than 30 percent. The maximum increase was found in the range of 6–8 percent under high volume condition and 50 percent MPR.

A model for predicting change in fuel consumption was developed in this study. The model shows that the probability of platoon formation, time spent in platoon, platooning configuration, and traffic conditions are all influencing the fuel consumption performance. The model can be used for economic analysis such as the estimation of time to recoup investment cost of the platooning system.

Finally, the study results are still limited to several assumptions. Future research should consider expanding the limit on platoon size, consideration of platoon restricted lane, and the effects of ramp traffic on vehicle throughput and fuel consumption performance.

CHAPTER 5: SYSTEM DEVELOPMENT FOR TRUCK PLATOONING DEMONSTRATION

The research team, in collaboration with the subcontractor and industry members of the project (TRW, Navistar, Denso, Bendix, Lytx, TARDEC, ANL, Great Dane), performed the preliminary analysis of requirements and specifications that will be used later in the project for system development. This chapter summarizes the following system development efforts:

- Define operational requirements.
- Perform preliminary safety analysis.
- Develop system specifications.
- Acquire equipment.
- Define technical demonstrations and operation demonstrations.
- Validate requirements.

DEFINE OPERATIONAL REQUIREMENTS

The scope of the requirements presented (see Appendix B) refers to the operational and functional requirements of a platooning system for the purpose of a proof-of-concept demonstration. They in no way define system and vehicle architectures, component specifications, or the implementation of software and its algorithms. Different modes of operation such as joining platoon, lateral acceleration, or platoon maximum speed were identified and used to design and operate the system.

PRELIMINARY SAFETY ANALYSIS

Potential hazards and risks due to platoon system malfunction or failure that could pose a safety threat to the environment, operator, and other road users are identified in this document. Also, safety goals are established, which will be later used in addressing the identified risks. Example of risks and hazards identified in this task include, but are not limited to, "collision, lane or road departure due to FV driver not ready/able to take over manual control" or "collision with trailing FV if gap is small."

SYSTEM SPECIFICATIONS

The technical specifications of the vehicle, control system, and subsystem actuators/sensors that convey the expected behavior of the motion controller are defined in Appendix D. The specifications also capture the requirements to addresses vehicle technical specifications (such as base vehicle, communication interface, safety monitoring, fault detection) and subsystem technical specifications (such as electronic control unit [ECU], emergency stop, HMI, motion controller).

EQUIPMENT ACQUISITION

Equipment acquisition begun as the project commenced in April 2015. Two Navistar ProStar 2012 models were secured as platform vehicles. Two 48 ft Great Dane Trailers were also made available to the project research team. Several other engineering equipment and supplies were procured (such as a Novatel DGPS, dSpace controllers) by either TTI or the subcontractor. Other equipment donated by the industry partners have either been installed (Bendix Wingman Fusion, TRW Electronic Power Steering) or are planned for installation in the near future (Lytx DriverCam, Denso DSRC Radio).

DEFINE TECHNICAL DEMOS AND OPERATION DEMOS

Appendix D addresses the requirements necessary to meet the constraints of the Phase I Proof-of-Concept system demonstration location. During the project planning phase, the project team assumed the TTI Riverside Test Bed Facility in Bryan, Texas. After a thorough consideration of this location versus other potential sites within Texas, the team decided to procced with the TTI Riverside Test Bed as the primary option. This demonstration specification defines the maneuvers that will be performed by the systems, range of performance, and the characteristics of the demonstration site. Opportunities and limitations associated with the specific site are discussed in Chapter 8: Truck Platooning Phase 1 Demonstration.

VERIFICATION OF REQUIREMENTS

The project team performed requirements verification throughout various phases of system development and integration. This included verification through simulation, SiL, and HiL testing, as well as in-vehicle system and operational tests performed at various test facilities. The project team also conducted vehicle integration activities and software development. In general, performance and other characteristics of the vehicles and trailers need to be obtained through dynamic driving, using real-time capture and various data analyses techniques in conjunction with subjective observations. A preliminary verification test plan was developed and verification tests were performed. This test plan is shown in Appendix D.

CHAPTER 6: FUEL SAVINGS AND EMISSIONS MEASUREMENT

INTRODUCTION

The research team primarily collected and analyzed data related to vehicle operation during the Phase 1 Demonstration. While this initial phase of testing is geared more toward proof-of-concept validation, it nonetheless offers an opportunity to collect relevant data on truck platooning as implemented for this project. In addition to the obvious desire to collect information on operation and basic energy usage from the demonstration event, the instrumentation and data collected also serves as a proof-of-concept to help identify areas of interest for expanded testing in possibly later stages of the project and related platooning work.

For both the LV and FV in the platoon, the project proposed to collect under the hood engine temperature measurements during the two-truck platooning demonstration event.

This represented a change to the original work plan, prompted by a project team conclusion that effects of platooning on fuel savings is well researched and other efforts are also underway to even further investigate the topic. Hence, given the available resources and the format of the final demonstration, it was deemed more valuable to investigate the impact of platooning on the vehicle's engine heat. The significance of the proposed approach is to better understand the impact of platooning on engine temperature, which as a result translates directly to changes in NOx emission, a topic that has not been sufficiently addressed in the literature.

DEFINITIONS/PROJECT PLAN

Since the end goal for Phase 1 was demonstrating system capabilities as opposed to high-speed track testing, the focus for the instrumentation and analysis tasks is on obtaining useful data while laying the groundwork to identify and develop more detailed instrumentation and testing plans for future project developments. This work, as a result, sought to use a fairly streamlined set of instrumentation for testing, seeking to avoid larger-scale instrumentation that would be mismatched to the type of testing used for this initial Phase 1 demonstration. With this streamlined focus in mind, this project used:

- Information provided by the vehicle's SAE J1939 communications bus.
- Instrumentation of signals focused on a preliminary assessment of under-hood temperatures associated with the LV/FVs within a basic platoon.

Data Acquisition

Allowing for a wide-range of signals to be collected in a single, time-synchronized storage location is key to collecting data that are useable for later in-depth analysis. With this issue at the forefront, this project used an Ipetronik logging system and related components to collect and store data taken during the demonstration event.

Communication Bus Logging

As mentioned in the previous section, one of the major focus areas of instrumentation for this project is the ability to log messages via the vehicle's communication buses. Specifically, the SAE J1939 bus protocol that is a CAN based reference commonly used in medium and heavy duty vehicles. Information related to vehicle operation, energy usage, and subsystem states is available via the 1939 bus, and this information was logged to aid in the assessment of vehicle energy usage and operation during the demonstration phase. As discussed previously, information was collected for both the LV and FV to their relative operation and efficiency can be compared over the course of the demonstration testing.

Under-Hood Temperature Data Collection

Several recent vehicle platooning studies have shown that elevated under hood temperatures that can lead to reduction in the expected benefits due to limited air-flow available to the trailing vehicle and resulting increased cooling system operation. This preliminary assessment work supplemented the information collected via the vehicle communications busses with actual temperature instrumentation located with the engine bays of the two evaluation vehicle. Similar to the global positioning system (GPS) and bus information, these data were logged and synchronized using a common data acquisition interface. While this testing and instrumentation was preliminary in nature, it offered some of the first data related to vehicle under-hood temperatures during platooning.

INSTRUMENTATION

To help summarize the main data collection components, Figure 22 shows an example of the hardware that was slated for this testing. Instrumentation specific to this project shown in Figure 22 have been highlighted in red.

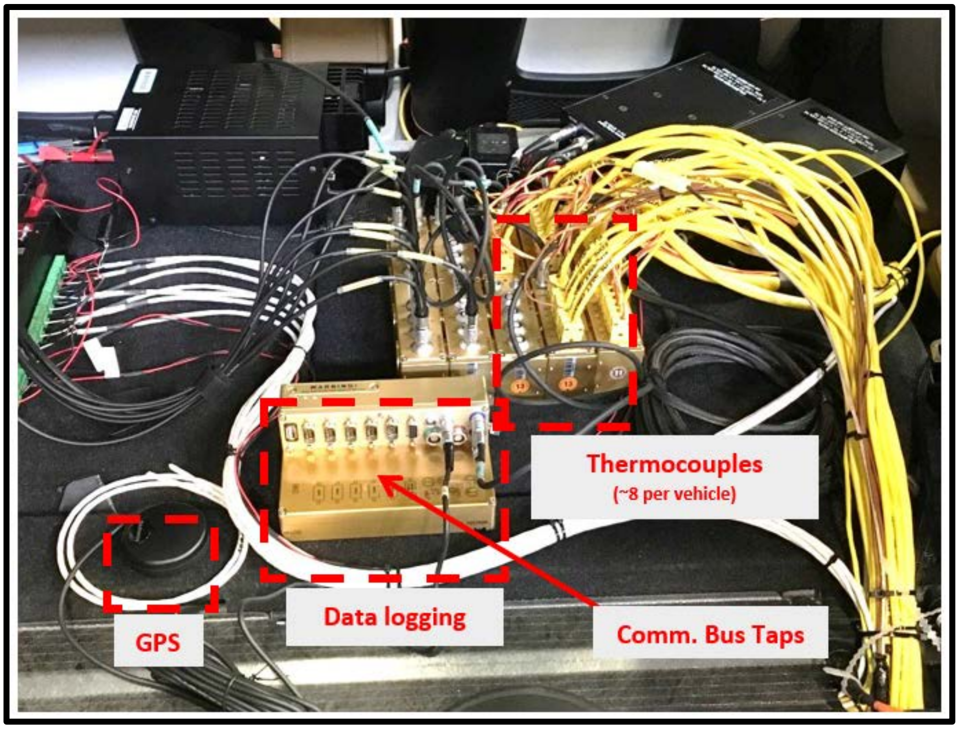


Figure 22. Project Specific Instrumentation.

Given the focus on thermal behavior doing the proof-of-concept demonstration, thermal nodes were instrumented for both the LVs and FVs. Thermocouples were then aggregated with via an Ipetronik in-vehicle data acquisition system, which stores the information locally and allows for time synchronization between modules. The Ipetronik modules are robust across a wide range of temperatures and are excellent candidates to be installed under-hood, despite the elevated temperatures. In addition to the thermal sensing, GPS information (lat./long./alt., speed, and UTC time) was also logged to visualize how the LVs and FVs were operating. Additionally, the UTC time signals recorded for each vehicle can be used to synchronize the collected data between the LV and FV. Thermal nodes selected for instrumentation during these preliminary efforts included:

- Center radiator.
- Driver side radiator.
- Behind fan.
- Air intake.
- Engine hoist.
- Valve cover.
- Firewall.
- Intake passenger side.

Figure 23 through Figure 28 show some of the instrumentation installed on-vehicle to provide some context relative to the integration efforts necessary to obtain this preliminary set of data. In future testing, more invasive and extensive thermal instrumentation is strongly recommended to better quantify temperatures related to the vehicles specific working fluids (coolant/oil) and the long-term temperature profiles for specific vehicle components with heat loading sensitivity, such as the 12V batteries and engine-boosting hardware.

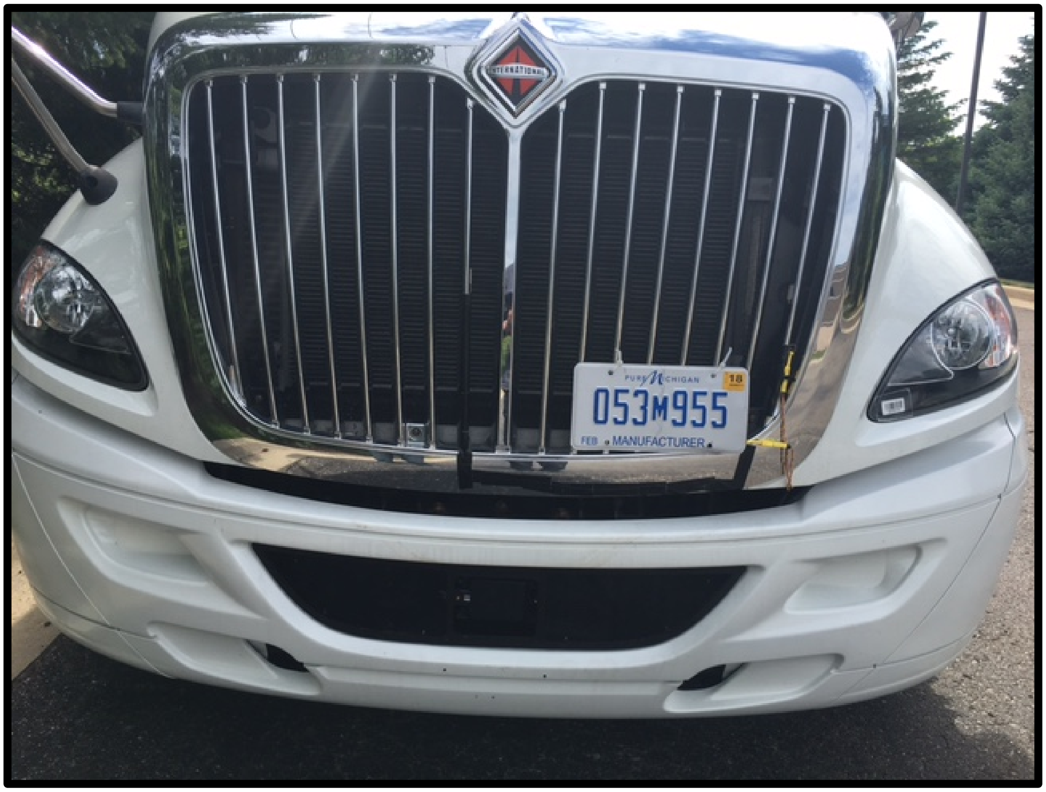


Figure 23. Radiator Inlet Instrumentation.

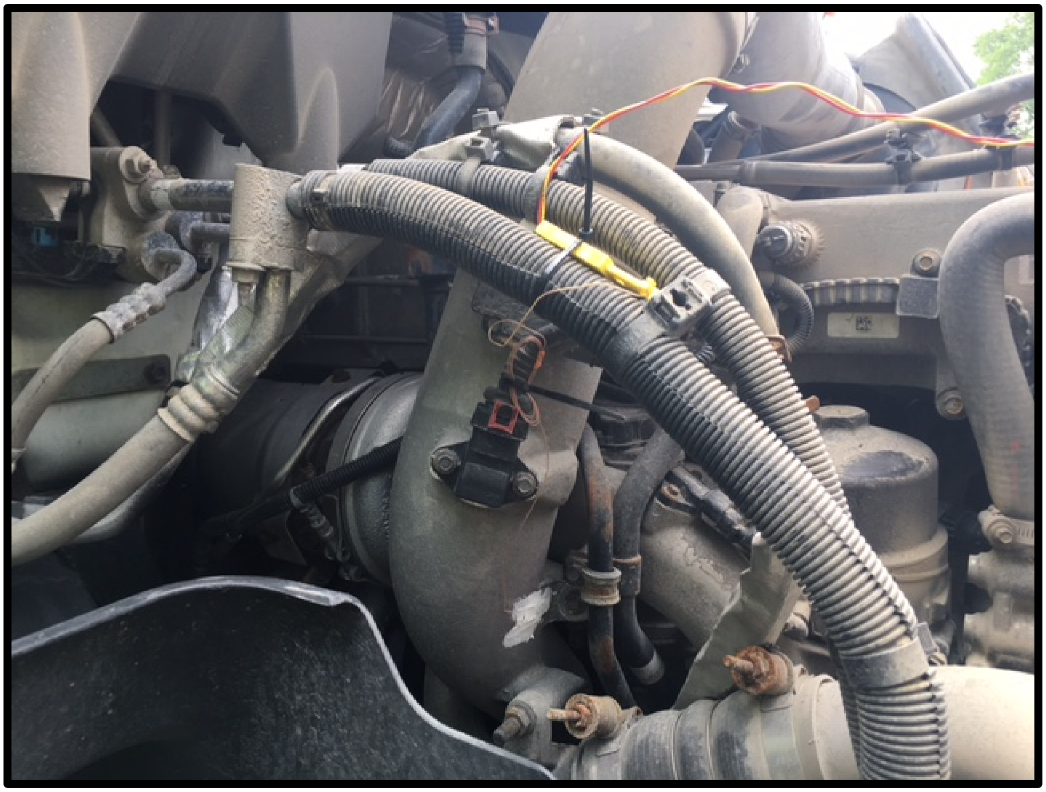


Figure 24. Passenger Side Intake Air Measurement.

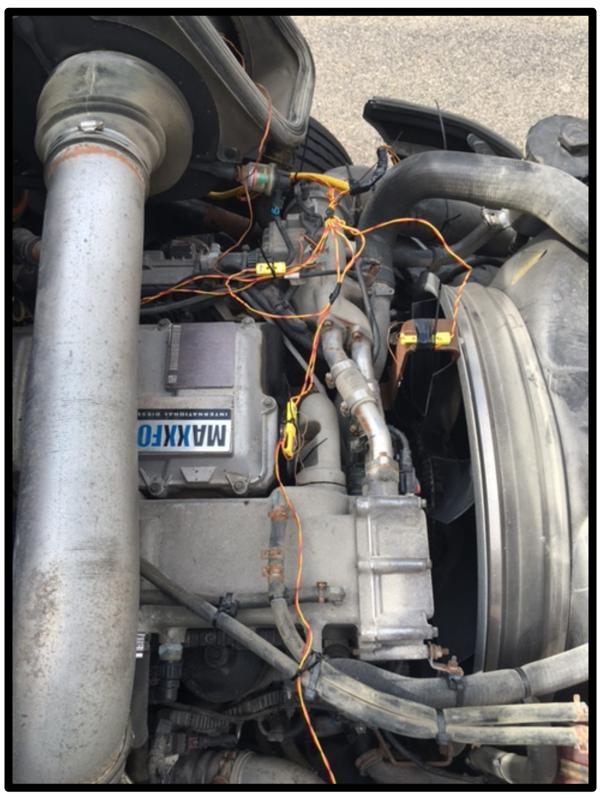


Figure 25. Fan Outlet and Intake Air Instrumentation.

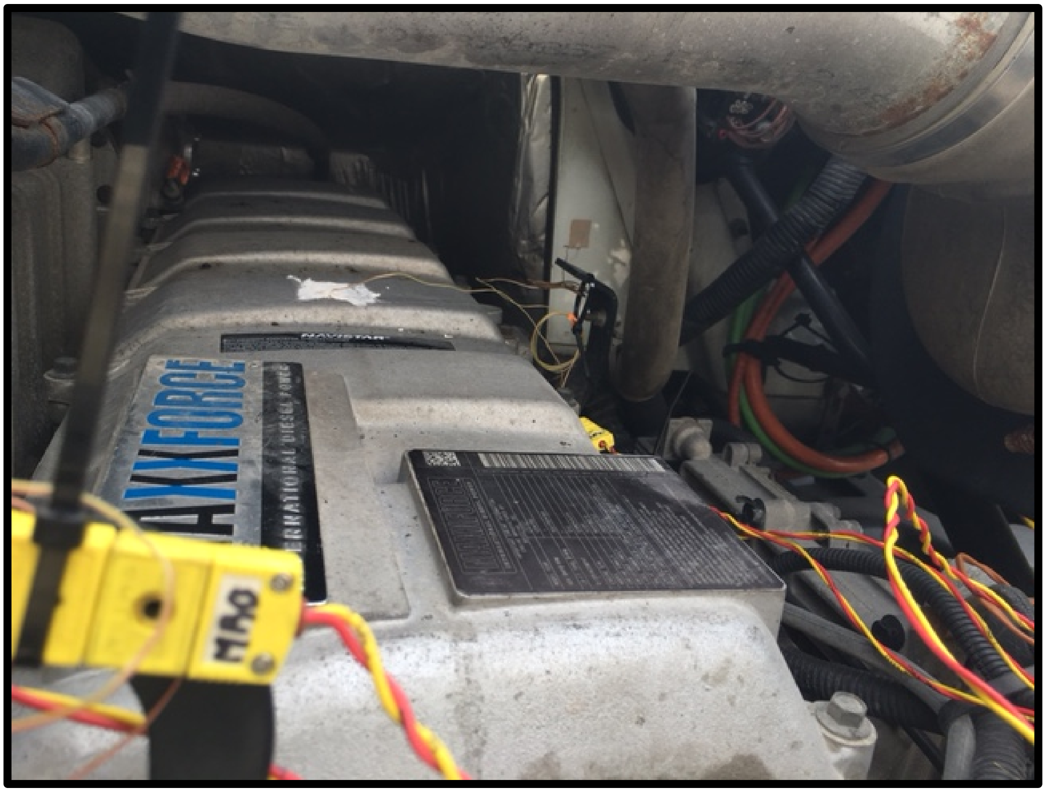


Figure 26. Valve Cover Temperature.


Figure 27. Overview of Under-Hood Instrumentation.

Figure 28. Thermocouple Aggregation and Logging (Open Ports Shown for Voltage/Current Sensing Shown But Not Used during Demo Event).

DATA COLLECTION AND ANALYSIS

Data gathered from the demo event were logged on individual CF cards stored in each reader. Upon completion of testing, the team transferred these data to a common location accessible by the research team members. While more analysis is forthcoming, the following plots seek to highlight some of the interesting observations from the demo event.

Figure 29 shows the FV’s temperatures across the entire day of the demonstration. While additional analysis is forthcoming, operational issues such as cooling fan operation and changes in intake air can easily be observed during the testing. Interestingly, the vehicle intake air temperature actually appears to reduce slightly while the vehicle is in motion (platooning) as evidenced by the drop in intake air temperature at roughly 8500s and 10000s. As would be expected, component and under-hood temperatures generally increase during vehicle operation, but not to a degree that would suggest significant airflow reduction in the FV (although following distance for this test was relatively generous for vehicle airflow).

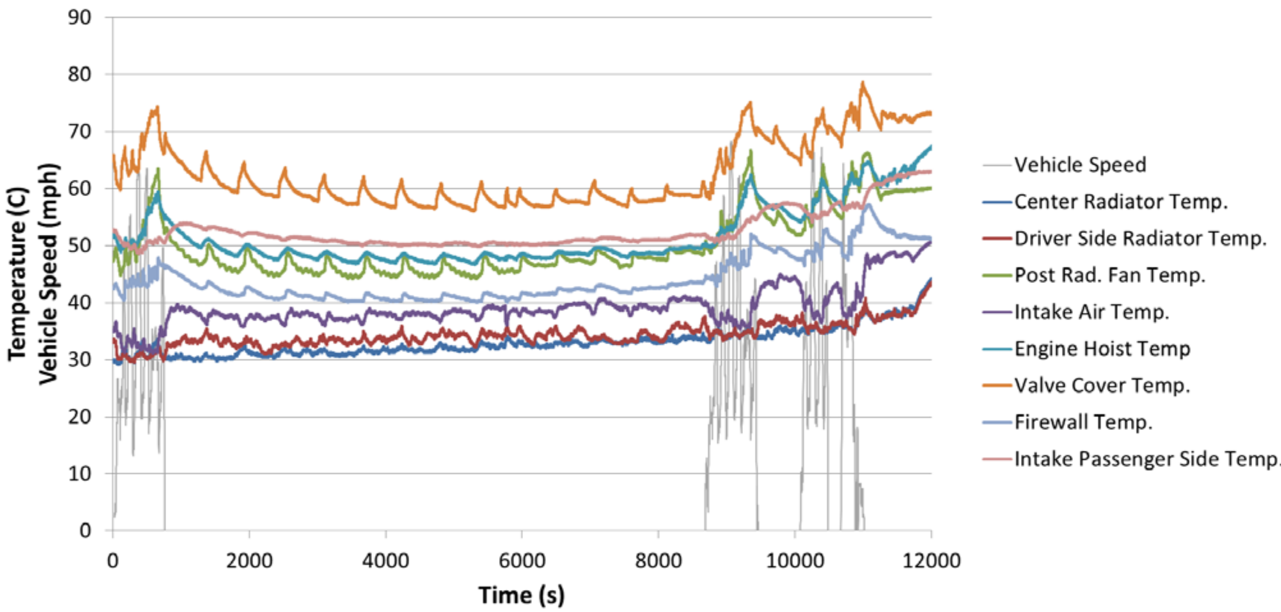


Figure 29. FV Thermal Data for Duration of Testing.

One interesting observation during testing was that the FV's front grill became quickly covered with a moderate amount of debris during the relatively short demonstration time. As shown in Figure 30, quite a bit of dry grass and other debris was spread across the vehicle grill after platooning operation. While somewhat obvious in hindsight, this observation again highlights some practical issues related to in-field platooning and the need to mitigate any excessive debris that may be transferred from the LV to the air intake/front grill of the FVs.

Figure 30. FV Front Grill Showing Accumulated Dirt and Debris.

The following four figures show GPS information from the demonstration testing. Figure 31 shows the GPS information from the entire demonstration day (i.e., looping the track several times). Figure 32 shows the latitude and longitude from the figure-eight maneuver, where the tight and consistent positioning of the vehicles can be observed even during turning events. Similarly, Figure 33 again shows consistent vehicle following during the lane-change maneuver. Last, Figure 34 provides a position snapshot at several time steps during the gap-closing maneuver that saw the FV close the gap relative to the LV.

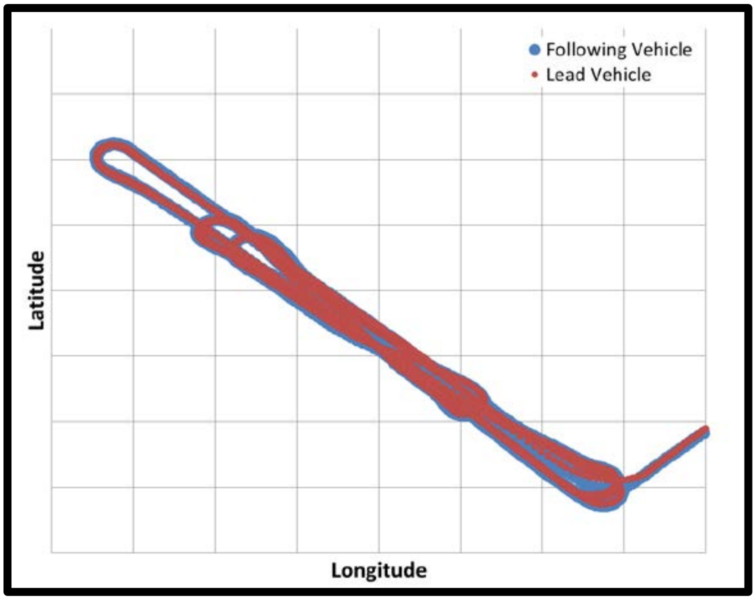


Figure 31. Overview of GPS Information for Entire Demo.

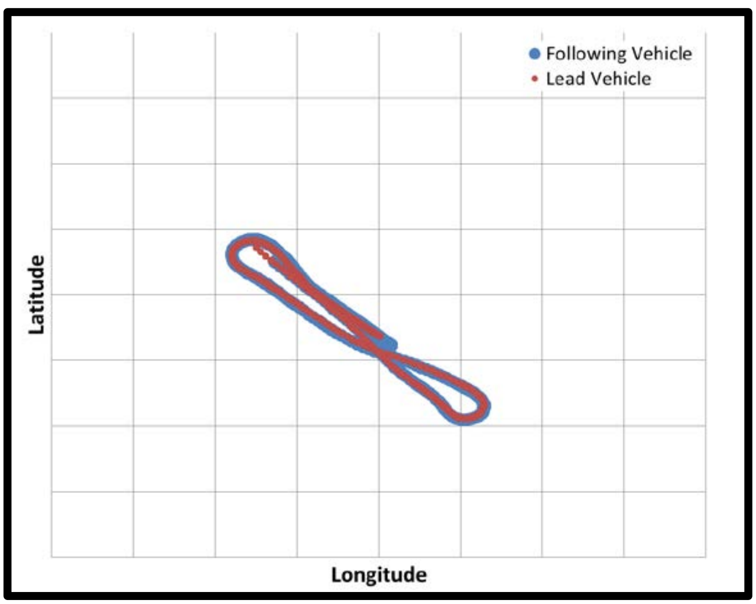


Figure 32. Figure-Eight Maneuver GPS Information.

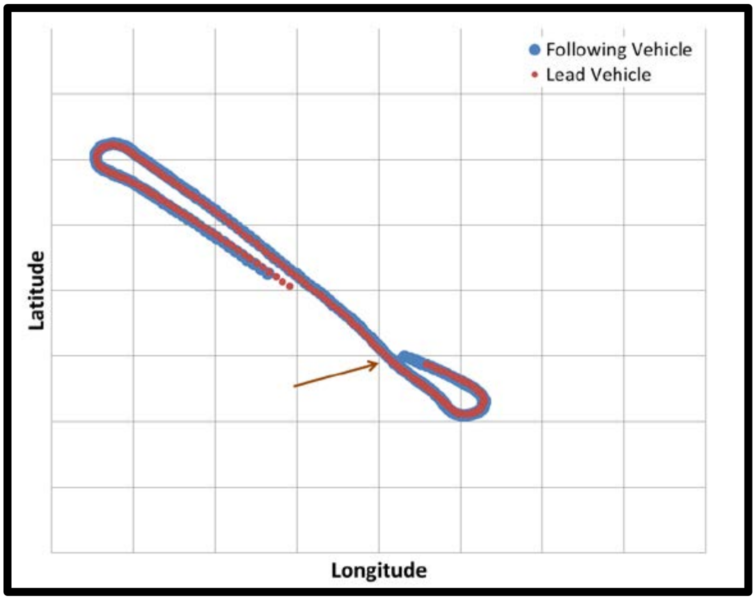


Figure 33. Lane-Change GPS Overview.

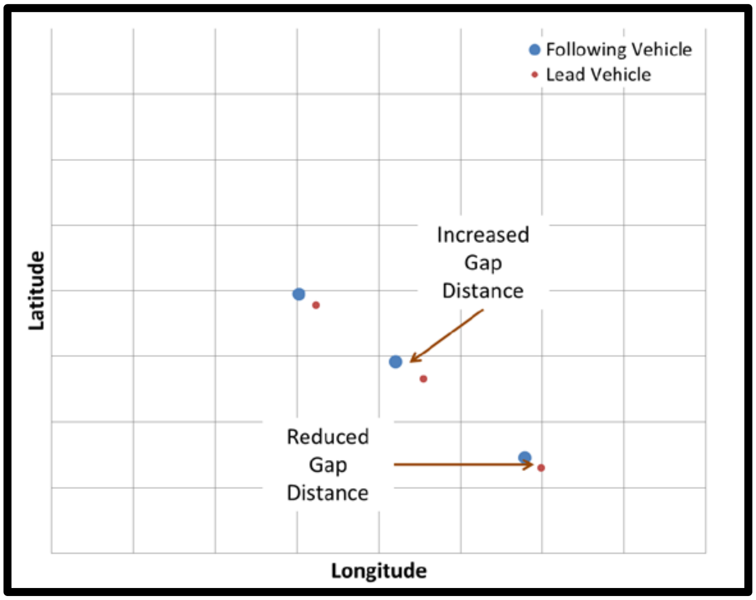


Figure 34. GPS Position Snapshot during Gap-Reduction Maneuver.

Figure 35 shows the vehicle speed for both the LV and FV as well as an estimated following distance between trucks during the main section of the demonstration. In the figure, the vehicle is operating in platooning mode, as evidenced by a relatively consistent following distance. Similarly, when the gap distance was increased for the gap increase-closure maneuver, it is clearly visible in the plot at roughly 9300s.

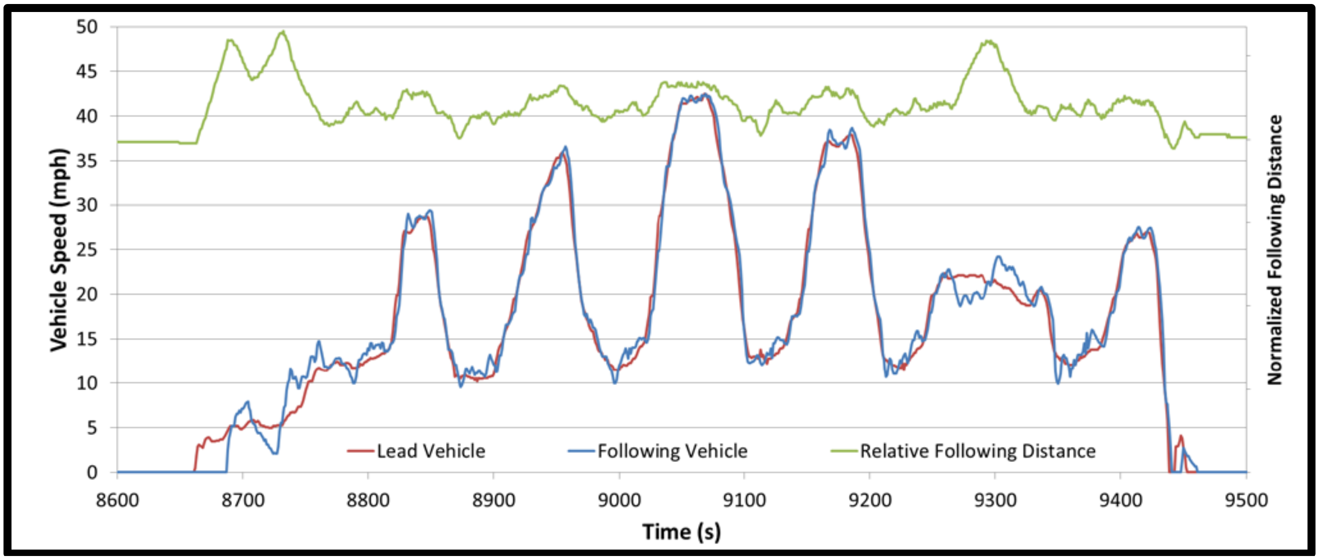


Figure 35. LV and FV Speed and Normalized Following Distance during Demo Event.

While GPS data are typically somewhat noisy, a common data acquisition and GPS antenna placement between the LV and FV aids in gaining some insights relative to the following truck's behavior as it platoons with in conjunction with the LV. As shown in Figure 36, the FV's speed trace appears to be a bit less smooth as compared to the LV. As would be expected, the FV must work to keep a consistent gap between vehicles while responding to variations from both the LV and the surrounding operating conditions (i.e., track surface). While the FV is generally pretty consistent relative to the LV, it does appear that the FV's speed is a bit noisier as compared to the LV. How this variability impacts fuel consumption and driver perception across a range of operating scenarios is of great interest to both this current analysis and any additional research related to this project.

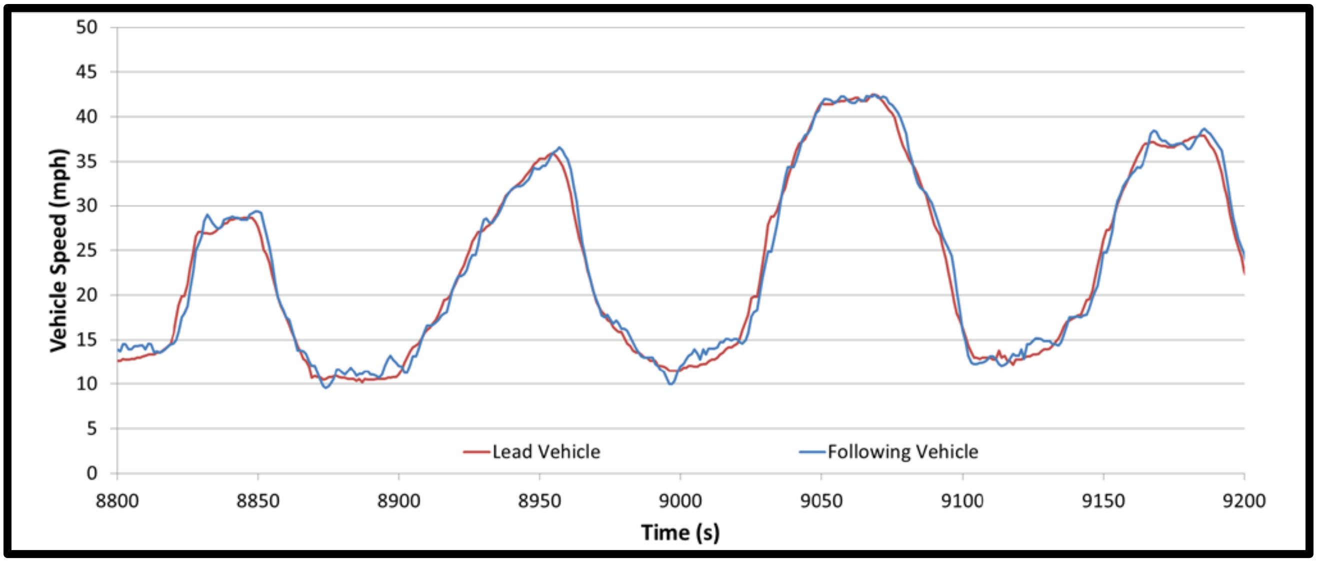


Figure 36. Highlighted LV and FV Speed.

Although useful and interesting data were collected during the demonstration via the previously installed instrumentation, unfortunately, two difficulties arose during testing and were not able to be debugged without interfering with the data collection efforts and the on-going demonstration. First, in addition to logging the temperature data, the data acquisition system were also configured to log the vehicle CAN network to collect additional information (including approximate fueling and some additional temperatures) during the demo to facilitate analysis. Unfortunately, when the data-file for recording this information was added to the loggers prior to the day of the demonstration, they both crashed and needed to be manually recovered and rebooted through a somewhat cumbersome process. In order to collect some data, a decision was made to omit the CAN logging at this point in time, while retaining the ability to do so in the future once the issues were debugged.

Second, although the LV was also instrumented using the same thermocouple placement as the FV, the thermocouple logging equipment appears to have encountered communications issues since the information was not being relayed to the main storage unit. Although this problem was known prior to the testing, it required removing the logging equipment from the vehicle and was undesirable given the need for data collection during testing. This logger/aggregator equipment is now being debugged (problem still unresolved) in order to be available for future testing purposes. These issues aside, the data collection and analysis efforts at this stage appear promising both in terms of highlighting new research directions and solidifying some of the concepts related to vehicle platooning.

PRELIMINARY CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

While limited somewhat in scope due to resource constraints and some untimely instrumentation issues, the data collected from this activity have been an interesting component to the overall successful demonstration of a truck platooning, which includes the ability to steer, control vehicle acceleration, and braking. Moreover, this work has identified several interesting issues and results from this initial round of testing:

- At following distances on the order of 50 ft (15 m), there does not appear to be significantly elevated temperatures in the FV. In fact, some signals appear to indicate somewhat cooler air as compared to the air temperatures during vehicle idle.
- While the demonstration testing did not see any adverse thermal impacts to the FV, a significant amount of debris was lodged in the front grill of the FV after a relatively small amount of operation. This strongly suggests the need to better understand methods to avoid debris getting lodged into a FV's grill and air intake system during in-field platooning service.
- The analysis shows that the demonstration vehicles appeared to follow each other very closely in terms of positioning (latitude and longitude). Even in relatively tight turns, the FV held the turn shape very closely and showed little to no oscillation in steering input and direction of travel.
- The vehicles appear to keep a relatively consistent gap length in addition to spatial positioning. That said, some additional vehicle speed noise was observed in the FV as it platooned with the LV. It is unknown if this is related to vehicle capability, controls settings, or (more likely) a mix of several factors. The trade-offs between following gap consistent, system performance, and driver/passenger perception of driving are of great interest as platooning begins to be evaluated across a wider range of operating conditions.

Given the successful completion of the platooning demonstration, a wide range of additional research experiments and instrumentation is applicable for additional phases of testing (with an expansion of scope and resources). Highlighted research suggestions include:

- Testing at a wide range of vehicle operating speeds and following distances to understand the interactions between vehicle usage, following distance, and efficiency.
- Data acquisition using more extensive thermal instrumentation and during extended operation at varying usage levels and following distances to study potential thermal limitations on platooning in greater detail.
- Testing with identical LV/FV and mixed platoons of both light-duty and medium/heavy-duty vehicles would provide some interesting insights into the possible real-world ramification of platoon fleets being generally available to the driving public.

- The sensitivity of a platoon to varying levels of vehicle performance-related characteristics, such as loading, braking performance, and engine horsepower. Furthermore, developing methodologies for assessing a vehicle's performance in real-time while integrating this information into the platooning controls and synchronization (i.e., if a much lower performance vehicle joins a platoon).
- Using a vision system or related instrumentation to collect real-time data on public roads to identify platooning opportunities and the real-world applicability of platooning across a range of regions and usage cases.

CHAPTER 7: TRUCK PLATOONING DEMONSTRATION PREPARATION

INTRODUCTION

As part of the project, the research team integrated the platooning systems and components (e.g., a proof-of-concept system) into the two demonstrator vehicles. This included the generation of engineering drawings and documentation; the design, development, and integration of the hardware and control algorithms; and operational and safety testing of the final system.

SYSTEM DESIGN AND IMPLEMENTATION

The system design and integration involved designing the hardware and control algorithms defined within the System Specification, creation of the Subsystem Technical Specifications, and development of the control algorithm requirements. The necessary hardware design involved:

- Creating electrical schematics.
- Creating wire harness drawings.
- Packaging of components.
- Design of mechanical bracketry and interface hardware.

The subtask required the control algorithms to be developed for the functions defined within the control algorithm requirements. This included using a mix of model based and straight C algorithms with modeling-in-the-loop (MIL) and hardware-in-the-loop (HIL) testing to minimize the time required for control algorithm debugging on the vehicle. Specific activities associated with this subtask included the generation of control algorithm and a MIL and HIL.

Given the unique nature of the project, and level of unknowns and uncertainties associated with each step of the development process, the team used a systems engineering process to establish a base architecture for the system and identify associated risks. Initial models were developed to address longitudinal control, lateral control, and the overall platoon control (i.e., a supervisory/information fusing controller) using a variety of inputs from vehicle controller area network (CAN), sensors, and actuators to process and estimate the state of the vehicles. The primary objectives were the successful fusion of all the information and the creation of a verifiable and testable closed-loop model.

The simulation was developed using TruckSim, a common simulation platform that provides methods for simulating the performance of multi-axle commercial and military vehicles, offering the ability to both simulate vehicle dynamics and develop the control system and algorithms. Figure 37 and Figure 38 show examples from the project simulation.

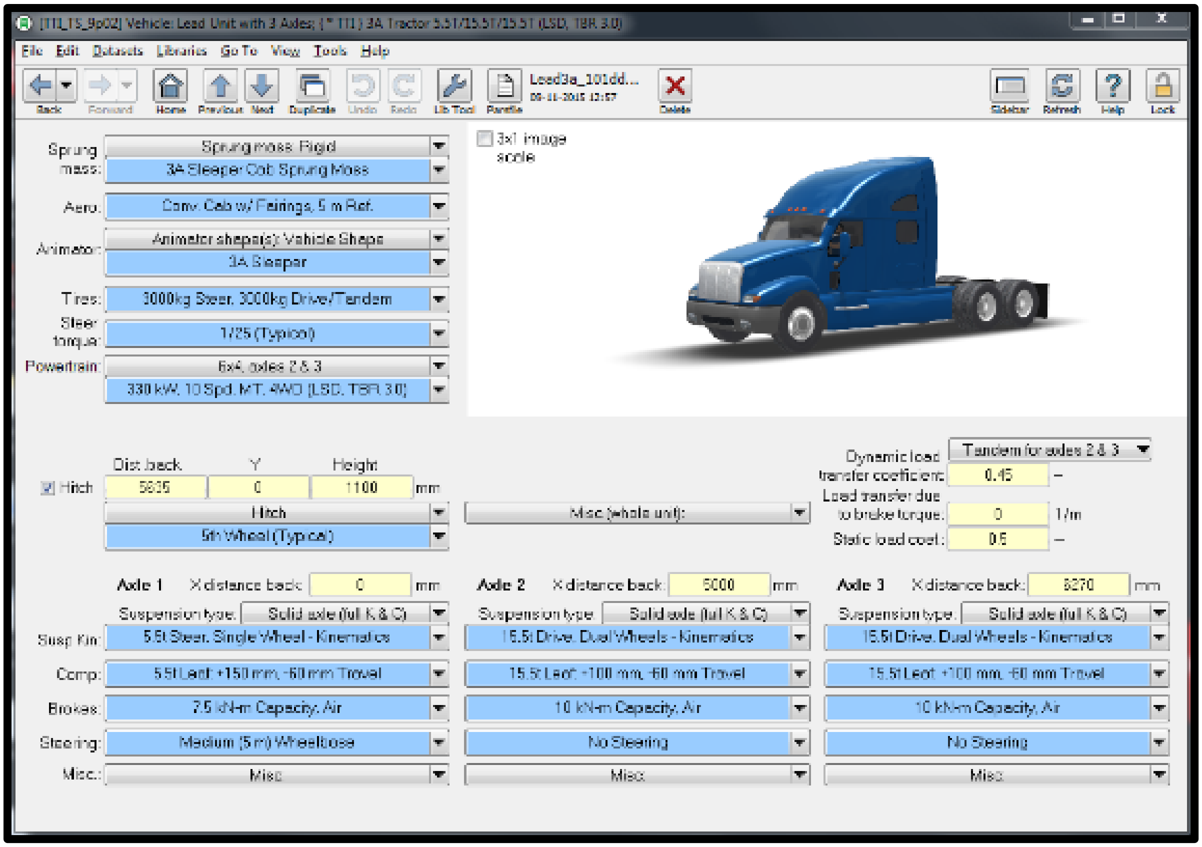


Figure 37. TruckSim Calibration Interface for Commercial Truck Platooning Development.

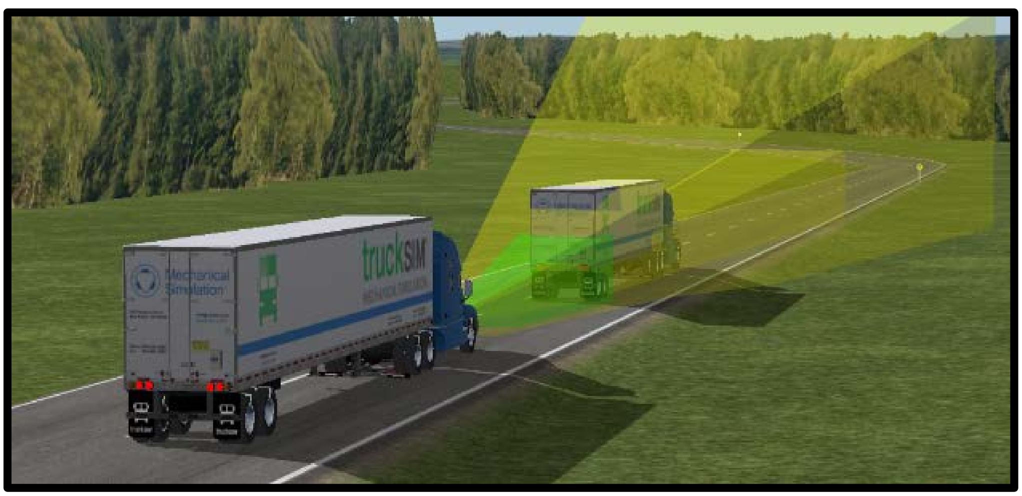


Figure 38. TruckSim Simulation Run for Commercial Truck Platooning Development.

The simulation and development tools included models for sensor fusion, Kalman filtering for position estimation, vehicle dynamic models, state space vehicle model, and others. These models were tested and verified in software-in-the-loop (SIL) and/or MIL environments as feasible. An iterative development process led to the refinement of the preliminary models and identification of additional signals (i.e., information from vehicle network and/or sensors) to improve the accuracy, efficiency, and reliability of the system.

VEHICLE INTEGRATION

The project progress led to an update to the System Specification Document and the creation of a Subsystem Technical Specifications Document (see Appendices B) that provided input to guide the system design and implementation, particularly from the hardware perspective. Hence, the following hardware was deemed necessary to satisfy the system requirements, leading to subsequent efforts to generate specifications, identify sources, procure, and ultimately install them.

Steering

An electronic steering system with high performance reliability is necessary for this platooning system. Two ColumnDrive systems were acquired from ZF-TRW, which are capable of providing full access and control to the steering. Although these were production components, they were not designed for this particular make/model of vehicle. Consequently, the installation required fabrication of bracketry and significant modification to the trucks. To accomplish this, both trucks were shipped to ZF-TRW facilities in Lafayette, Indiana, to remove the existing steering columns, fabricate brackets, and components, and then install the ColumnDrives. Given the packaging of the ColumnDrive and the need to maintain its functionality, a new driver dash module had to be sourced and acquired from Bendix. Fortunately, the team was able to acquire a pre-existing driver dash module from a previous project, eliminating significant component lead time. Figure 39 shows the ColumnDrive system and installation.

Figure 39. ZF-TRW ColumnDrive System and Installation.

Braking

To ensure safe and reliable operation of the entire system, the team decided to use the vehicle network to actuate the brakes. Hence unlike acceleration (described below), all the commands could be sent via CAN messages, and no external control system equipment was needed to achieve the necessary functionality.

Acceleration

Platooning requires precise control over the gap between the LV and FV. Hence, a reliable yet accurate system was deemed necessary to fulfill this objective. An alternative analysis was performed to identify the best option and, given the availability of CAN information and engineering resources, a linear actuator (see Figure 40) was chosen as the most viable option to control the acceleration profile (i.e., control the gas pedal) of the FV.

Figure 40. Linear Actuator for Acceleration Control.

Communication

To ensure robust performance of the system (e.g., high precision positional accuracy of the FV for following lateral and longitudinal trajectories) and fulfill the system performance requirements for joining or dissolving the platoon, wireless communication between the two vehicles is necessary. A Denso DSRC radio and DSRC antenna was added to each truck, providing the capability to send SAE J2735 compliant messages between the two vehicles. Figure 41 shows the installation of the DSRC antennae on the driver's side-view mirror.

Figure 41. DSRC Antennae Installation (See Arrow).

Collision Mitigation

Based upon engineering analysis, the team decided to integrate the platooning system on top of the existing collision mitigation system. Both trucks were shipped to Ohio to receive upgraded Wingman Fusion Collision Mitigation technology at Bendix facility. Figure 42 provide a depiction of the Wingman Fusion Collision Mitigation system components and the sensor fields of view.

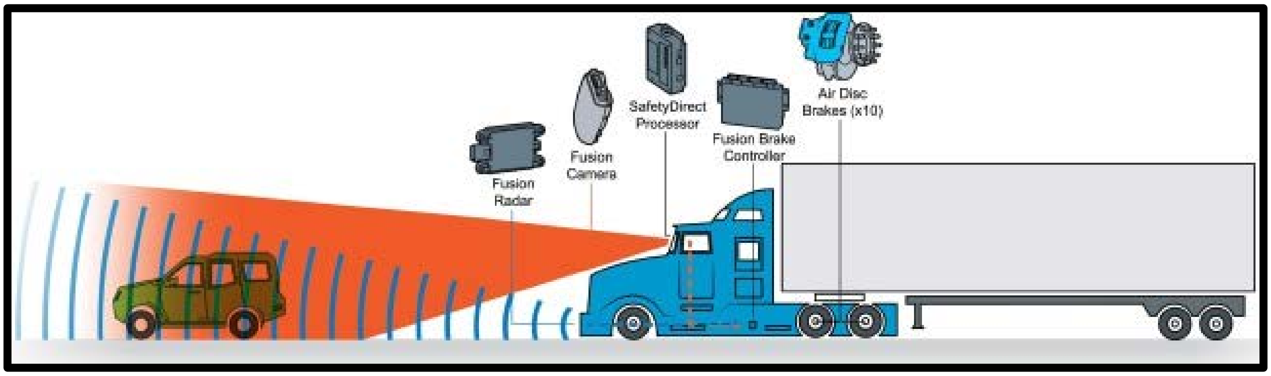


Figure 42. Bendix Wingman Fusion Collision Mitigation System.

Navigation

Engineering analysis concluded that a differential GPS solution is necessary in order to increase the precision of the (trailing vehicle's) system while following the LV's trajectory. Hence two Novatel FlexPak6 solutions were obtained and one was installed on each vehicle. Figure 43 shows the installation of the Novatel FlexPak6 (see arrow).

Figure 43. Bendix Wingman Fusion Collision Mitigation System.

Ranging

To maintain the desired gap between the two vehicles while in platoon formation, a ranging solution was needed. A combination of the radar and camera provided by the Bendix Wingman Fusion with the Novatel DGPS provides the necessary accuracy and reliability for measuring the distance between the LV and FV.

Driver Vehicle Interface

An important aspect of the system effectiveness is communication the status of the system to the driver and enabling him/her to control certain aspects of the system. To accomplish this, a Beijer embedded operator panel was installed in each vehicle. Figure 44 shows the specific Beijer operator panel and installation in one of the project vehicles.

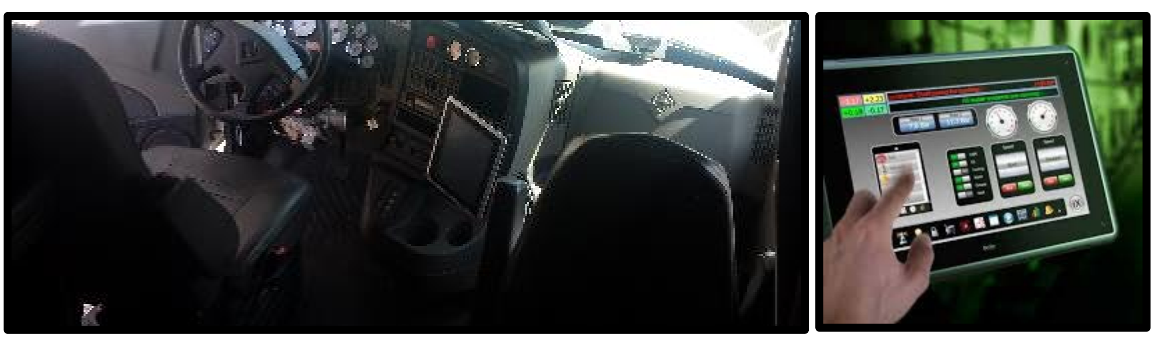


Figure 44. Beijer Embedded Operator Panel and Installation.

Driver Monitoring

The driver plays a critical role in platooning and maintaining his/her vigilance and oversight of system performance is crucial, particularly when operating a proof-of-concept system. Lytx provided and installed a DriveCam driver monitoring system that records the scene inside the cab and the driver's view of the road when specific calibratable thresholds are exceeded or triggered. Examples include emergency events such as hard braking or sudden acceleration. When the DriveCam is triggered, it records the scenes and transmits them to a backend processing system. The unit is mounted up on the center of the wind shield, as shown in Figure 45.

Figure 45. Lytx DriveCam Installation.

Emergency Stop

In the event of an emergency or the occurrence of a safety-critical fault, the system should incorporate a means to easily disengage the entire platooning system and bring the vehicle back to its normal mode of operation promptly and gracefully. A red emergency stop (eStop) button, or mushroom button, was installed in the driver dashboard area of each vehicle as a countermeasure for such situations. This eStop button provides the drivers with the option to safely and promptly take over the control when operating in platooning mode. The eStop system severs the platooning system from the vehicle control system, allowing the vehicle to fall back into its default mode of operation (i.e., manually driven and as if platooning was not installed). Figure 46 shows and example of the eStop switch installed in each truck.

Figure 46. eStop Switch.

Electronic Control Unit

An ECU was installed in the LV to collect and process data about the state of the LV (i.e., vehicle speed, heading, yaw, GPS position, and GPS time prior to transmitting to the FV). An

ECU was also installed in the FV to perform the same tasks, in addition to performing the platooning control algorithm processing tasks. The research team assessed several options prior to selecting, purchasing, and installing dSpace MicroAutobox units. Figure 47 shows a dSpace MicroAutobox and the specific installation in one of the project vehicles. This installation is directly behind the driver's seat.

Figure 47. dSpace MicroAutobox and Installation.

Power Supply

During the development phase, a separate source of power supply and associated convertors were needed in order to run some of the equipment (e.g., laptops). Hence convertors and batteries were obtained and installed to provide a power source for the development equipment. Figure 48 shows the installation of the power supply and converters.

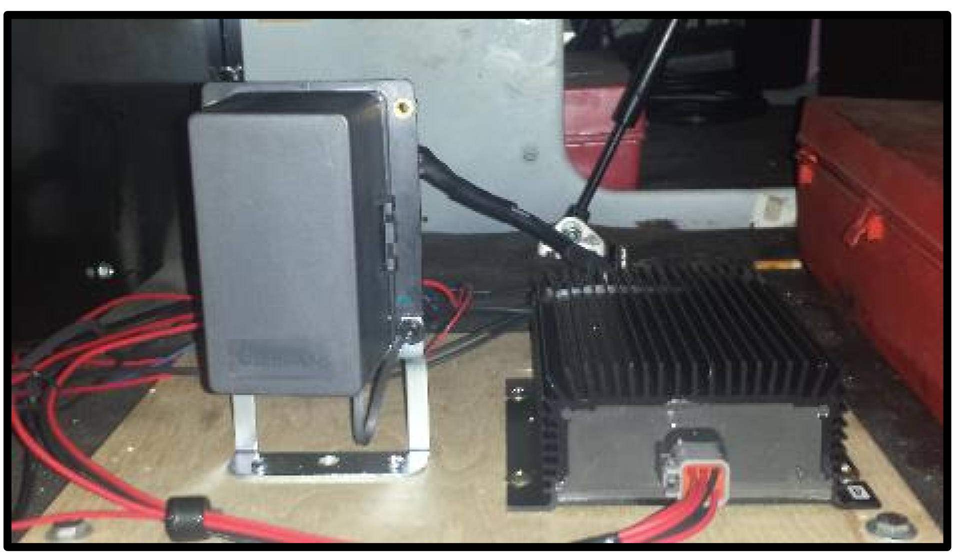


Figure 48. Power Supply and Converter Installation.

Hardware Integration

Once all the hardware was installed, an overall integration effort was required to connect all the sensors and actuators to the ECU, close the control loop, and make the system executable. This integration was consistent with the system architecture that was developed earlier in the project. Figure 49 depicts the overall hardware integration.

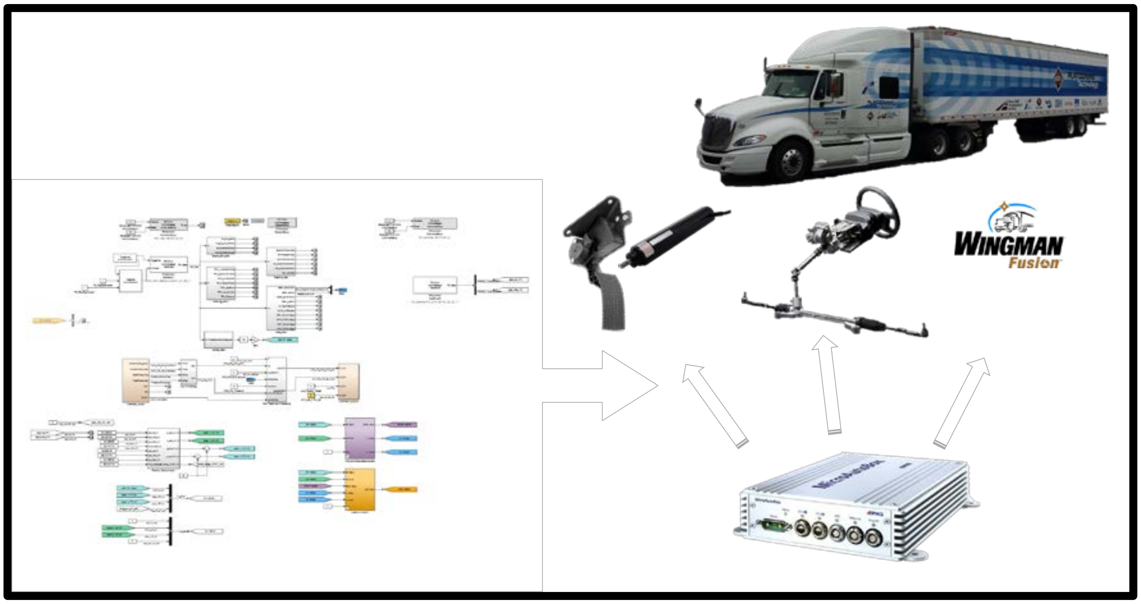


Figure 49. Hardware Integration.

INITIAL SAFETY AND OPERATIONAL TESTING

The research team performed initial safety and operational testing, including specification of verification methods, procedures, and acceptance criteria to ensure that the system functions safely and reliably. This effort used tools and techniques developed in the preceding subtasks, such as SIL, MIL, and HIL testing, in addition to test track testing.

After the initial control models were developed and verified by MIL and SIL testing, the controls were integrated into the ECUs. Two separate development efforts were required, one for the LV and another for the FV. Following this integration, a series of bench-top tests were performed to ensure proper communication and feedback among the components of the overall system.

At the component level, however, no testing was deemed necessary since all the components and equipment used for this effort were either mass production units or mature prototype units (i.e., DSRC radios) developed prior to this research project. Nevertheless, some modifications were necessary to address issues that emerged, such as:

- The ECU timing out and shutting down the system.
- The DGPS output being in an incompatible format for the ECU.
- Several iterations of firmware necessary to ensure proper operation of the DSRC radios.

Following the bench top tests and in-vehicle verifications, the vehicles were taken to Michigan Technical Research Park (MTRP) located in Ottawa Lake, Michigan. This facility provided a dirt track and an oval track that were suitable to further develop, calibrate, and fine tune the system. Figure 50 shows the oval test track at MTRP, including an overheard view of the entire oval and a view from inside the cab of the trailing vehicle while testing in platooning mode.

Figure 50. MTRP Oval Track and View of the Oval While in Platooning Mode.

The project team performed the remaining task 7 system integration and development at this facility. This included calibration of the lateral and longitudinal control modules. Integration and testing of the platoon controller, integration and testing of the HMI, then a final session of fine-tuning control models on the test roads. Following a TTI buy-off ride on July 14, 2016, the vehicles were shipped to Bryan, Texas, to prepare for the Phase I demonstration.

As a final step in the system integration task, the project team updated the following platooning specification documents to reflect the final Phase I Proof-of-Concept system design:

- RD15-001714-1 CG011851 TTI Platooning Vehicle and Subsystem Technical Specification (see Appendix D).
- RD15-001716-1 CG011851 TTI Platooning Operational Requirements Specification (see Appendix D).
- 2016 0125 RD15-001733-1 CG011851 TTI Platooning Demonstration Specification (see Appendix D).

Results from the final verification are provided in shown in Appendix D.

CHAPTER 8: TRUCK PLATOONING PHASE 1 DEMONSTRATION

INTRODUCTION

This chapter discusses the proof-of-concept demonstration and workshop that built upon the results of feasibility studies and knowledge gained during the design, build, development, integration, and testing of the prototype proof-of-concept systems into two class 8 commercial vehicles. The prototypes developed for this demonstration were intended to provide a sense of real experience expected from the final product by demonstrating the capability to successfully perform the necessary platooning functions in a controlled test track environment. The event was brought together major stakeholders for a workshop in conjunction with the demonstration to disseminate the project results to the stakeholders and obtain their feedback. The event informed TxDOT and USDOT of the state of the practice and implications of truck platooning applications on its future planning activities, from operational and maintenance perspectives.

PHASE 1 DEMONSTRATION

Following the completion of the integration, testing, and development, the project team conducted a proof-of-concept demonstration of the commercial truck platooning – level 2 automation and an associated workshop in College Station, Texas. The event was held at the Texas A&M University System (TAMUS) RELLIS Campus in Bryan, Texas, on July 22, 2016, and was attended by over 60 representatives from TxDOT, FHWA, TAMUS officials, TTI executive leadership, and the project team. The event began at 9:30 a.m. at the Texas A&M Engineering Extension Service (TEEX) Central Texas Police Academy facility, and Table 29 shows the activities.

Table 29. Demonstration Event Schedule.

Time	Event	Location
9:30 a.m.	Registration and Morning Refreshments	Front Lobby
10:00 a.m.	Welcome and Introductions	Classroom D
10:15 a.m.	Phase 1 Project Overview	Classroom D
	Phase 2 Project Concept	
11:05 a.m.	Board Shuttles to Test Facility	Runway Tent
	Static Demonstration	
	Field Demonstration	
12:30 p.m.	Lunch	TEEX
1:30 p.m.	Demonstration Debrief and Q&A	Classroom D
2:15 p.m.	Adjourn	

Details of the proof-of-concept demonstration and workshop for the commercial truck platooning—level 2 automation project are summarized below.

PROOF-OF-CONCEPT DEMONSTRATION

The TTI RELLIS facility was chosen for conducting the demo in order to provide both a controlled environment in the interest of public safety and a controlled test track. An access-controlled portion test facility was used to conduct a closed test track and controlled environment for public safety. The project team elected to contain the entire demonstration to Runway 22, one of the shorter runways on the RELLIS facility, shown in blue in Figure 51. This 5000 ft long and 300 ft wide runway allowed adequate space to perform all scenarios, provided an area in which the vehicles remained within view, and while minimizing the run time for each compared to alternatives. The capabilities of the system allowed the team to demonstrate the scenarios on approximately 3900 ft (approximately ¾ mile) of the runway, as shown in the dashed lines in Figure 51. An observation area was placed near the center of the test loop. The TTI Truck Platooning Demonstration Specification is in Appendix D.

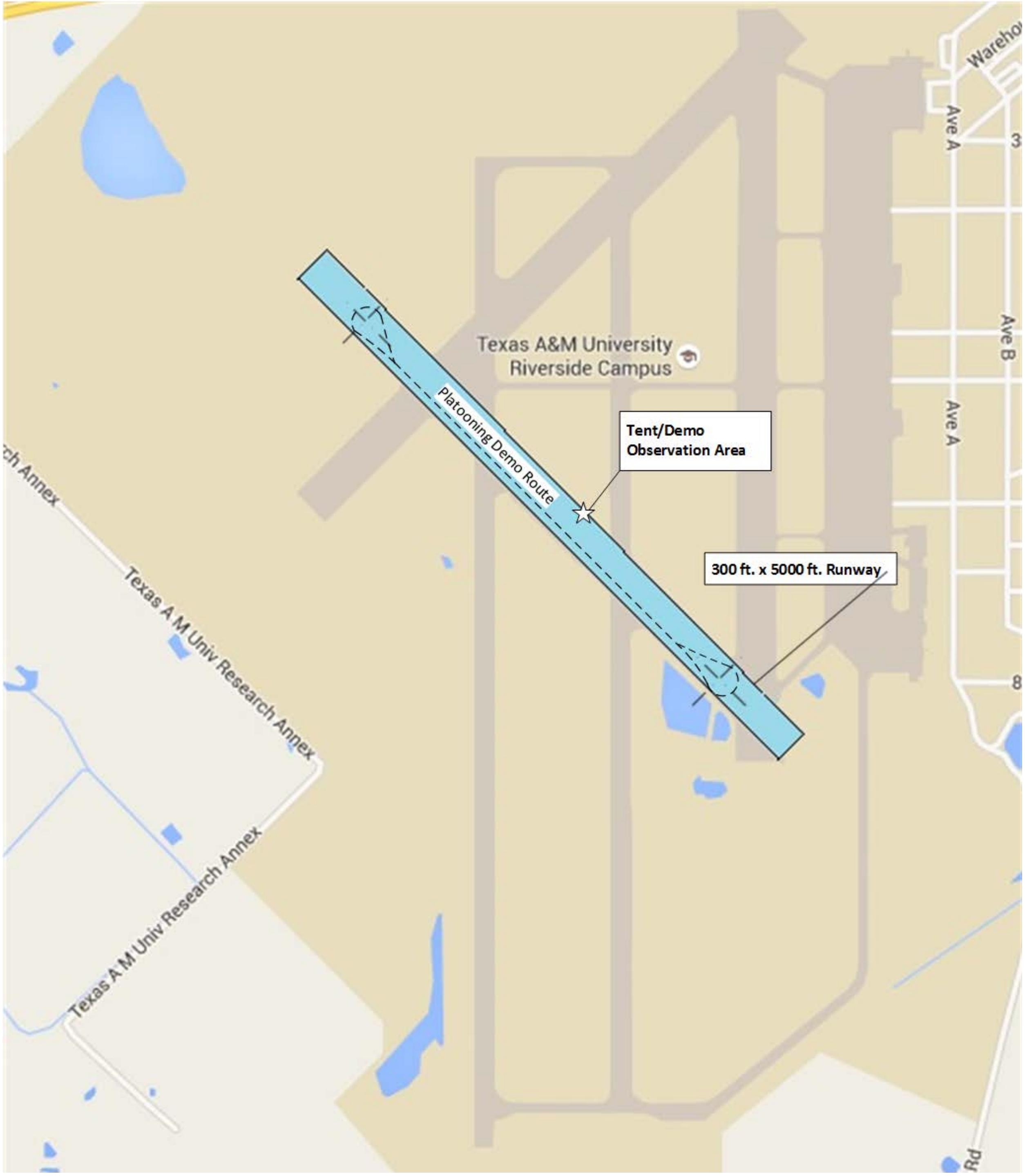


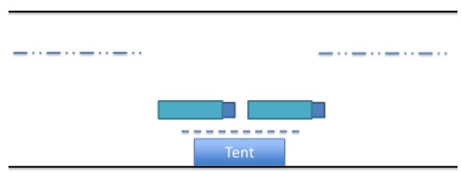
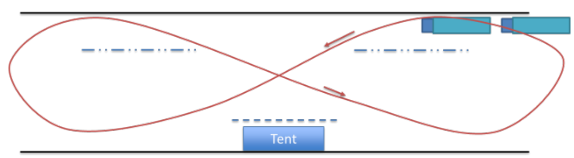
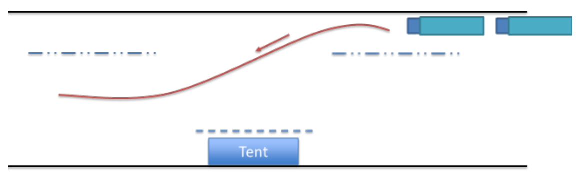
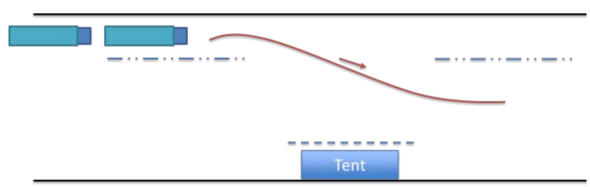
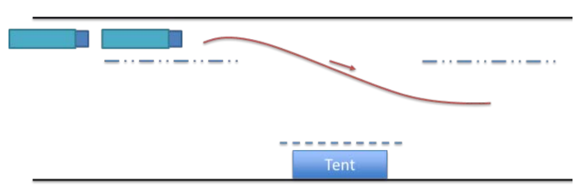
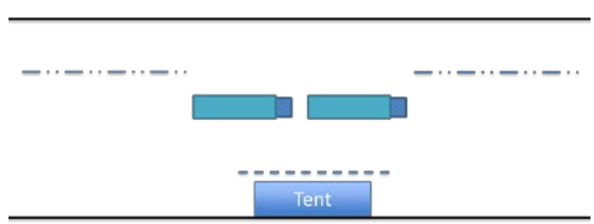
Figure 51. Platooning Test Area at the TAMU RELLIS Campus.

The demonstration began with a static viewing of both vehicles near the observation area, allowing attendees to take a close look at the technology and systems installed in the vehicles and discuss the details with the project team. Figure 52 shows the static demo set-up.

Figure 52. Commercial Truck Platooning – Level 2 Automation Demonstration, College Station, Texas.

The static demonstration was followed by dynamic scenario demonstrations on runway 22. Table 30 provides depictions of the maneuvers that were demonstrated by the vehicles.

Table 30. Demonstration Maneuvers.

Demonstration	Maneuver Diagram
Static Viewing	
Join and Figure 8 Join: Requested/accepted @ 0 mph Form: Transition to Automated Platoon mode above 5 mph Figure 8 Speed=20 mph Figure 8 Gap=15 ft	
Left Lane Change Speed=40 mph Gap=15 ft	
Right Lane Change Speed=40 mph Gap=15 ft.	
Gap Increase Speed=40 mph Gap=15 ft increased to 50ft.	
Stop in Formation Speed=40 mph to 0 mph Gap=15 ft.	

In the first maneuver, Join and Figure-8[11], the FV requested to join a platoon[12] with the vehicles in a stopped position, the LV accepted the request, the vehicles began driving toward the northwest (NW) end of the test route with the FV entering a transitional control mode above 5 mph and then forming the platoon once the system conditions are met for transition to autonomous (e.g., platooning) mode. At this point, the control system on the FV assumed autonomous control of acceleration, braking and steering, maintaining lateral alignment, and following at a the 15 m gap as selected by the FV driver. The LV driver then maneuvered the platoon through a figure-8 pattern, traveling from the NW end of the test route to the southeast (SE) end and then back to the NW end, maintaining a maximum speed of 20 mph in the straight-away sections. During the maneuver, the FV maintained proper lateral alignment and longitudinal spacing relative to the LV, demonstrating the capability of the system to accurately and autonomously follow a LV in formation. This fundamental capability was corroborated in the remaining scenarios.

Also notable, this scenario established the capability for the system to form a platoon in approximately 3/8 mi., or half the distance of the test course, beginning from a stopped position with adequate time to reduce speed and change directions. Finally, the scenario revealed the system capability to negotiate tight turns (i.e., less than 150 ft radius) at low speeds without disbanding (e.g., breaking) the platoon, two capabilities that extend well beyond those necessary to operate platoons on limited access highways, as currently envisioned for a future Phase 3 pilot deployment with a commercial freight operator in Texas.

For the second and third scenarios, the platoon performed a Left Lane Change and a Right Lane Change, respectively, while maintaining the 15 m gap setting and traveling 40 mph. To improve the participants' perspective from the observation area, a line of cones was placed along the centerline of the two adjacent lanes, with a gap of less than 100 ft (e.g., a section without cones) aligned with the center of the viewing area. As the platoon executed the left lane change within the gap, the cones prior to the lane change remained visible to the observers as the platoon passed them, but those immediately following the lane change were blocked from their view by the platooning vehicles. Similarly, the cones prior to the right lane change were blocked, while the cones immediately following the maneuver remained in view. Table 30 provides an illustration for each scenario, with the two line segments representing the cone placement. The fourth maneuver involved increasing the gap between the vehicles from 15 m to 50 m while traveling 40 mph. The final scenario demonstrated the capability for the platoon to decelerate

[11] Detailed technical information on the system operations, including definitions, modes and transitions between modes, is available in the Ricardo document **RD15-001716-1 CG011851 TTI Platooning Operational Requirements Specification 08012016** in Appendix D of this report.

[12] Detailed technical information on the specifications and procedures associated with each functional scenario in the Phase 1 demonstration, including particular system settings, driver and system actions/reactions and other conditional information is available in the Ricardo document **2016 0125 RD15-001733-1 CG011851 TTI Platooning Demonstration Specification v8 08012016** in Appendix D of this report.

from 40 mph to a stop with the FV remaining in autonomous mode and maintaining formation, a scenario that further demonstrates capabilities beyond those planned for Phase 3 deployment.

Since it was not feasible to provide the participants an opportunity to ride in the vehicle for the Phase 1 demonstration, the project team considered alternatives to demonstrate the in-vehicle experience. The team chose to capture video footage during a demonstration preparation session on June 20, 2016. With the support of the TTI Marketing and Communications, video was capture from various in-vehicle and external views, including the following:

- FV driver's hands and feet off of the controls.
- LV and FV driver input to the driver-vehicle-interface.
- FV driver view ahead.
- View of FV from LV trailer.
- External view of both vehicles from a chase vehicle.
- External view from above with the support of the TAMU CANVASS lab unmanned aerial vehicle lab.

A video was produced showing multiple superimposed views for each demonstration scenario. This video was included as part of the pre-demo briefing. Figure 53–Figure 57 show frames from the video for some of the scenarios.

Figure 53. Demonstration – Join Platooning.

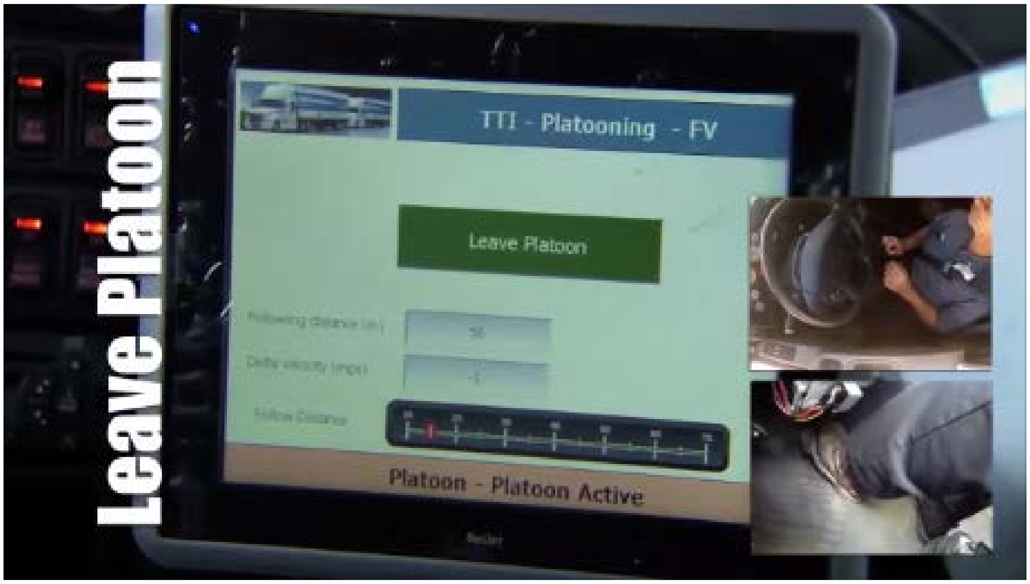


Figure 54. Demonstration – Leave Platooning.

Figure 55. Demonstration – Following.

Figure 56. Demonstration – Change Gap.

Figure 57. Demonstration – Lane Change.

The demonstration was successful and proved the concept that commercial trucks can platoon in level 2 automation. Following the field demonstration, the participants were shuttled back for lunch and the final workshop session.

WORKSHOP AND DEMONSTRATION CLOSE-OUT MEETING

As part of the overall event, the project team held workshop in conjunction with the demonstration aimed at disseminating the Phase 1 project results to project stakeholders and obtaining their feedback. Although essentially encompassing the entire event, the workshop primarily included two elements, a briefing on platooning technology and the project results, combined with the session at the end of the day, yet essentially included all activities associated with the event.

Upon arrival, participants were greeted by TTI administrative and event support staff. The event began with a briefing by the project leads that that included:

- A comparison of 0-6836 project platooning technology to other recent and ongoing commercial vehicle platooning automation research and demonstrations.
- Overview of the vehicle design and build.
- A summary of the statutory, regulatory, and legal liability research.
- An overview of the feasibility study.
- An overview of the demonstration, including video footage of all demo scenarios with multiple three to five of superimposed views below:
    - Driver view from FV.
    - Views of FV driver's hands and feet.
    - View of the driver-vehicle-interface.
    - Outside aerial view from UAV.
    - Outside view from a chase vehicle.
    - Outside view of the FV from the rear of the LV.
- An overview of the Phase 2 proposal.

A demonstration debrief and open discussion was held at the end of the day to allow the participants to provide input and ask the project team questions. A summary of the topics are as follows:

- Ability or desire to set gap from the front vehicle.
- Nighttime operations/implementation.
- Loading issues and LV vs. FV for optimal fuel savings, performance, and capabilities.
- Maximum/optimal length of platoons.
- Loads other than box trailers.
- Cybersecurity and hacking vulnerability.
- Applicability to manual transmission vehicles.
- Options for retrofit, certifications, regulations, etc.
- Cost-benefit vs. other efficiency improvements.
- Ongoing training/recertification.
- Weigh-in-motion, loading, impacts of platooning on truck/load behavior/load type.
- High speed testing/testing on grades.
- Interoperability.
- Impacts on geometrics, operations, etc.
- Failure mechanisms.

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APPENDIX A: FMVSS EXEMPTION REGULATORY PROCESS

APPLICATION FOR EXEMPTIONS[13]

(a) A manufacturer of motor vehicles or passenger motor vehicles may apply to NHTSA for a temporary exemption from any Federal motor vehicle safety or bumper standard or for a renewal of any exemption on the bases of substantial economic hardship, making easier the development or field evaluation of new motor vehicle safety or impact protection, or low-emission vehicle features, or that compliance with a standard would prevent it from selling a vehicle with an overall level of safety or impact protection at least equal to that of nonexempted vehicles.

(b) Each application filed under this part for an exemption or its renewal must—

(1) Be written in the English language;

(2) Be submitted in three copies to: Administrator, National Highway Traffic Safety Administration, Washington, DC 20590;

(3) State the full name and address of the applicant, the nature of its organization (individual, partnership, corporation, etc.) and the name of the State or country under the laws of which it is organized;

(4) State the number and title, and the text or substance of the standard or portion thereof from which the temporary exemption is sought, and the length of time desired for such exemption;

(5) Set forth the basis for the application and the information required by § 555.6(a), (b), (c), or (d) as appropriate.

(6) Specify any part of the information and data submitted which petitioner requests be withheld from public disclosure in accordance with part 512 of this chapter.

(i) The information and data which petitioner requests be withheld from public disclosure must be submitted in accordance with § 512.4 of this chapter.

(ii) The petitioner's request for withholding from public disclosure must be accompanied by a certification in support as set forth in appendix A to part 512 of this chapter.

(7) Set forth the reasons why the granting of the exemption would be in the public interest, and, as applicable, consistent with the objectives of 49 U.S.C. Chapter 301 or Chapter 325.

(c) The knowing and willful submission of false, fictitious or fraudulent information will subject the petitioner to the civil and criminal penalties of 18 U.S.C. 1001.

[13] See § 555.5

BASIS FOR APPLICATION[14]

(b) If the basis of the application is that the exemption would make easier the development or field evaluation of a new motor vehicle safety or impact protection features providing a safety or impact protection level at least equal to that of the standard, the applicant shall provide the following information:
(1) A description of the safety or impact protection features, and research, development, and testing documentation establishing the innovational nature of such features.
(2) An analysis establishing that the level of safety or impact protection of the feature is equivalent to or exceeds the level of safety or impact protection established in the standard from which exemption is sought, including—
(i) A detailed description of how a vehicle equipped with the safety or impact protection feature differs from one that complies with the standard;
(ii) If applicant is presently manufacturing a vehicle conforming to the standard, the results of tests conducted to substantiate certification to the standard; and
(iii) The results of tests conducted on the safety or impact protection features that demonstrates performance which meets or exceeds the requirements of the standard.
(3) Substantiation that a temporary exemption would facilitate the development or field evaluation of the vehicle.
(4) A statement whether, at the end of the exemption period, the manufacturer intends to conform to the standard, apply for a further exemption, or petition for rulemaking to amend the standard to incorporate the safety or impact protection features.
(5) A statement that not more than 2,500 exempted vehicles will be sold in the United States in any 12-month period for which an exemption may be granted pursuant to this paragraph. An application for renewal of such an exemption shall also include the total number of exempted vehicles sold in the United States under the existing exemption.

PROCESSING APPLICATIONS[15]

(a) The NHTSA publishes in the Federal Register, affording opportunity for comment, a notice of each application containing the information required by this part. However, if the NHTSA finds that an application does not contain the information required by this part, it so informs the applicant, pointing out the

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[14] See § 555.6

[15] See § 555.7

areas of insufficiency and stating that the application will not receive further consideration until the required information is submitted.

(b) No public hearing, argument, or other formal proceeding is held directly on an application filed under this part before its disposition under this section.

(c) Any interested person may, upon written request, appear informally before an appropriate official of the NHTSA to discuss an application for exemption or the action taken in response to a petition.

(d) If the Administrator determines that the application does not contain adequate justification, he denies it and notifies the petitioner in writing. He also publishes in the Federal Register a notice of the denial and the reasons for it.

(e) If the Administrator determines that the application contains adequate justification, he grants it, and notifies the petitioner in writing. He also publishes in the Federal Register a notice of the grant and the reasons for it.

(f) Unless a later effective date is specified in the notice of the grant, a temporary exemption is effective upon publication of the notice in the Federal Register and exempts vehicles manufactured on and after the effective date.

APPENDIX B: TASK 2 STAKEHOLDER INTERVIEW QUESTIONS

The following are the set of interview questions approved by the Texas A&M Institutional Review Board and used to guide the interviews with stakeholders.

1. Can you describe your organization and its activities?

2. Are you familiar with the concept of automated truck platooning?

3. Is your organization currently involved in truck platooning-associated activities? Are you aware of any other organizations that are engaged in truck platooning?

4. When discussing the concept of truck platooning, one of the most frequently mentioned areas of concern is liability. To help us better understand the trucking environment, can you describe the commercial trucking liability environment for your organization, or the typical liability environment for organizations in your field?

5. Is your organization concerned about liability issues related to truck platooning?

6. Does your organization have any plans to address these liability concerns? If so, what are they?

7. Are you aware of any arrangements between commercial trucking organizations or third-parties (like clearinghouses) that enable organizations to share, defer, or otherwise minimize liability for joint operations?

8. Are you aware of any laws that would prohibit automated truck platooning at the state or federal level?

These questions served as the structure for the interviews, although the applicability and usefulness of each question varied by respondent due to the diversity of the interview pool. Some questions also served as an opportunity to explain certain aspects of the project or platooning details (see question 2 for an example).

APPENDIX C: TASK 3 STAKEHOLDER INTERVIEW QUESTIONS

OPERATORS AND OWNER/OPERATORS

1. From the perspective of the trucking industry your company is a part of, what are the ***operational benefits*** (finance, legal, enforcement, equipment, etc.) to implementing truck platooning?

    a. What are the ***operational benefits*** (finance, legal, enforcement, equipment, etc.) to implementing truck platooning that are specific to your company?

2. From the perspective of the trucking industry your company is a part of, what are the ***safety concerns*** to implementing truck platooning?

    a. What are the ***safety concerns*** to implementing truck platooning that are specific to your company?

3. From the perspective of the trucking industry your company is a part of, what performance metrics would you look at for analyzing truck platooning?

    a. What performance metrics would you look at for analyzing truck platooning specific to your company?

4. From the perspective of the trucking industry your company is a part of, what are the concerns regarding regulatory enforcement of vehicles in truck platoons?

5. From the perspective of your company, at what level would you're your organization would the operational decision to create/join/leave a platoon be made (e.g., dispatch, individual driver)?

    a. If individual driver make the decision, would approval from dispatch be required?

6. From the perspective of your company, what level of real-time information (roadway and vehicle) would your operations center (or drivers) need (especially if additional to what they currently have) to make on-the-fly decisions about creating / joining / leaving platoons?

7. From the perspective of your company, are there minimum roadway and operating requirements that would have to be met before you would consider truck platooning? (e.g., speed, volumes, no lane closures, minimum trip length, minimum number of lanes)?

8. From the perspective of your company, where is the optimal place to form automated truck platoons? Dynamically on the road? At a rally point adjacent to a facility? At a warehouse or terminal facility?

9. From the perspective of your company, would you ever consider forming truck platoons with vehicles from other companies?

10. From the perspective of your company, do your current logistics and business practices provide you with enough trucks travelling over the same route at the same time to warrant truck platooning as a potentially viable mode of operation?

    a. How would your logistics planning need to change (if it does) to embrace the concept of truck platooning?

DRIVERS

1. Are you an independent owner/operator?

    a. If so, do you lease your vehicle to a larger company?

2. From your perspective as a professional truck driver, what level of real-time information (roadway and vehicle) would you need if you have to make decisions about creating / joining / leaving platoons?

3. From your perspective as a professional truck driver, are there minimum roadway and operating requirements that would have to be met before you would consider truck platooning (e.g., speed, volumes, no lane closures, minimum trip length, minimum number of lanes)?

4. From your perspective as a professional truck driver, do you see logistical issues with forming truck platoons with vehicles from other companies?

5. From your perspective as a professional truck driver, what safety concerns would you have regarding truck platooning

    a. How would they need to be addressed before you would consider this technique?

6. From your perspective as a professional truck driver, are there specific safety, regulatory, or monitoring equipment that your vehicles would need prior to participating in truck platooning operations?

7. From your perspective as a professional truck driver, what impacts (if any) do you see on FMCSA driver time and rest requirements from implementing truck platooning?

8. From your perspective as a professional truck driver, are there certain types of loads that should never be allowed in a truck platoon for safety or other reasons?

9. From your perspective as a professional truck driver, do you foresee any logistical / operational differences between flatbeds and trailers in truck platooning?

10. From your perspective as a professional truck driver, what training needs would you have pertaining to truck platooning

PUBLIC AGENCIES

1. From the perspective of a public agency, what are the ***operational benefits*** (finance, legal, enforcement, equipment, etc.) to implementing truck platooning?

2. From the perspective of a public agency, what are the ***safety concerns*** to implementing truck platooning?

3. From the perspective of a public agency, in which lane does it make the most logical sense to allow truck platoons to operate? Shoulder lane? Median lane? Exclusive truck platooning lanes?

4. From the perspective of a public agency, where does the responsibility fall to educate the public regarding truck platoons (their purpose, that they are allowed, how they operate, how to interact with them, etc.)?

5. From the perspective of a public agency, what level of real-time roadway information do you foresee having to provide to the trucking industry to enable them to make platooning decisions?

    a. What horizon (in time or distance) do you foresee having to provide this information?

    b. Is this a different level of information than you provide now?

6. From the perspective of a public agency, are there minimum roadway and operating requirements that would have to be met before truck platooning should be allowed (e.g., speed, volumes, no lane closures, minimum trip length, minimum number of lanes, etc.)?

7. From the perspective of a public agency, what safety concerns are present regarding truck platooning?

8. From the perspective of a public agency, what specific safety, regulatory, or monitoring equipment should/shall be on vehicles prior to allowing them to participate in truck platooning operations?

9. From the perspective of a public agency, how would truck platoons affect OS/OW regulations (e.g., OS/OW would not be allowed to join platoons, platoons not allowed on roads with OS/OW restrictions)?

10. From the perspective of a public agency, do you anticipate having to adapt or enhance your traffic incident management procedures to account for truck platooning operations?

LAW ENFORCEMENT

1. From the perspective of law enforcement, what are the ***safety concerns*** to implementing truck platooning?

2. From the perspective of law enforcement, what are the concerns regarding regulatory enforcement of vehicles in truck platoons?

3. From the perspective of law enforcement, how would you anticipate that the traveling public will react to truck platoons?

4. From the perspective of law enforcement, in which lane does it make the most logical sense to allow truck platoons to operate? Shoulder lane? Median lane? Exclusive truck platooning lanes?

5. From the perspective of law enforcement, where does the responsibility fall to educate the public regarding truck platoons? (their purpose, that they are allowed, how they operate, how to interact with them, etc.)

6. From the perspective of law enforcement, are there minimum roadway and operating requirements that would have to be met before you would consider truck platooning (e.g., speed, volumes, no lane closures, minimum trip length, minimum number of lanes)?

7. From the perspective of law enforcement, where would the optimum place to form truck platoons be? Dynamically on the road? At a rally point adjacent to a facility? At a warehouse or terminal facility?

8. From the perspective of law enforcement, are there specific safety, regulatory, or monitoring equipment that vehicles in truck platooning operations should be required to have?

9. From the perspective of law enforcement, are there certain types of loads that would never be allowed in a truck platoon for safety or other reasons?

The nature and applicability of each these questions may vary based on the particular stakeholder.

APPENDIX D: TTI PLATOONING VEHICLE AND SUBSYSTEM TECHNICAL SPECIFICATIONS

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TABLE OF CONTENTS

Version 1.0

1. INTRODUCTION

1.1. Revision History

Revision ID	Date	Issued by	Purpose
1.0	28-Aug-2015	Kimber	Initial release
1.1	4/3/16	Frikken -Shah	HMI Update

1.2. Purpose

The content of this document serves the purpose of expounding the planned description and architecture of the platooning control systems to be integrated into the two class 8 truck and trailers. Included in this document is the Vehicle Technical Specification (VTS), Subsystem Technical Specification (SSTS) and Interface Control Document (ICD). The compilation of these documents allows all the system information to be captured once in a single location for distribution and reference.

All requirements related to this project are laid out in the **TTI Truck Platooning Operational Requirements Document**. These include the operational, functional and performance requirements are used in the creation of the system specification. Any change in the requirements document may necessitate a change in the control system.

This document defines the interfaces between Platooning Control Modules, other electronic control units, and subsystem actuators and sensors. This covers the protocol used for communication, the data that will be transmitted, and the structure of the data messaging. It also covers discrete interfaces for controlling actuators and reading data from sensors. Software function may be included but will not initially be completely specified. As a more in-depth understanding of the actuator and sensor system and their abilities and limitations is formed the software specification will be developed.

It is expected that as the Control System is implemented and commissioned new information will become available which may necessitate a deviation from the required functionality described in this document, in which case the document will be updated. The document is not intended to prescribe a particular implementation. However, examples of the required functionality are illustrated by schematic pseudo-code to clarify understanding. In all cases, the text description of the functionality is the master.

Each paragraph in this document is categorized as follows:

- **For Information** – These paragraphs provide information only and are not, requirements, assumptions or limitations. NOTE: Paragraphs without an explicitly stated category (of which this paragraph is an example) are to be regarded as For Information.

- **Requirement** – These paragraphs describe required functionality. Where appropriate further information that is not itself a requirement is appended to the paragraph in *italics*.
- **Limitation** – These paragraphs document known limitations of the functionality as described or which will be acceptable in the implementation. Before implementation begins these limitations should be reviewed carefully, because changing or deleting the limitations may have a significant impact on the implementation.
- **Assumption** – These paragraphs document assumptions about the required functionality, development process or components external to the Control System.
- **Definition** – These paragraphs define terminology used elsewhere in the document.

1.3. Scope

This document is meant to describe the technical specification of the vehicle and control system, subsystem actuators / sensors and convey the expected behavior of the Motion Controller.

This specification may contain explanatory or exemplary items (text, figures, and tables) outside the technical specification. These explanatory and exemplary items are not part of the specification.

1.4. Audience

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1.5. Definition of Terms / Abbreviations

1.5.1. Levels of Obligation

Use of the words "shall", "should", "must", "will", and "may" within this Specification observe the following rules:

"Shall." The word *SHALL* in the text expresses a mandatory requirement of the Specification.

"Should" The word *SHOULD* in the text expresses a recommendation or advice on implementing such a requirement of the Specification, such recommendations or advice are expected to be followed unless good reasons are stated for not doing so.

"Will" The word *WILL* in the text expresses a requirement on the usage of the tool

"May" The word *MAY* in the text expresses a permissible practice or action. It does not express a requirement of the Specification.

1.5.2. Abbreviations

Term	Description
ABS	Anti-Lock Brake System
CAN	Controller Area Network

CCP	CAN Communication Protocol
DAS	Driver Alert System
DMS	Driver Management System
DSRC	Dedicated Short Range Communication
ECU	Engine Control Unit
EPAS	Electric Power Assisted Steering
ESC	Electronic Stability Control
FPCM	Follow Vehicle Platooning Control Module
FV	Following Vehicle in platoon
GPS	Global Positioning System
HMI	Human Machine Interface
IMU	Inertia Measurement Unit
LPCM	Lead Vehicle Platooning Control Module
LV	Lead Vehicle of platoon
PCM	Platooning Control Module
SSTS	Sub System Technical Specification
TCS	Traction Control System
TCU	Transmission Control Unit
TxDoT	Texas Department of Transportation
TTI	Texas Transportation Institute
V2V	Vehicle to Vehicle
VTS	Vehicle Technical Specification

1.6. References

ID	Document Source
RD15/001716.1	CG011851 TTI Truck Platooning Demonstration Operational Requirements Document
RD15/001733.1	CG011851 TTI Truck Platooning Demonstration Plan
RD15-001743-1	CG011851 TTI Preliminary Hazard Analysis

2. CONTEXT

2.1. Overview

The purpose of this document is to lay out the technical specifications, at the vehicle and subsystem level, for a two vehicle truck platooning demonstration for Texas Department of Transportation (TxDOT) and lead by Texas A&M Transportation Institute (TTI). The project's objective is to validate the feasibility and benefit of truck platooning. For this project, two Class 8 tractor trucks with trailers will be used. The first vehicle, the platoon Lead Vehicle (LV), is driven manually by a trained driver. The second vehicle, the Follow Vehicle (FV), has a driver but can be autonomously controlled to follow the path of the LV at a specified distance.

Additional partners were brought on to fulfill the platooning request as listed below:
Ricardo – Platooning control system integrator
TRW – Electronic power steering system manufacturer and integrator
Navistar – Engine manufacturer and vehicle provider
Denso – DSRC manufacturer and integrator
Bendix – Wingman Fusion and ABS/ESC/TCS Manufacturer and integrator
Lytx – Driver alert system manufacturer and integrator

The platooning control system will have means to control the steering, throttle and braking systems of the FV when engaged in a platooning with the LV. A trained driver will be able to, under certain conditions, engage platooning and join the platoon formed with the LV. Typically, a controller will communicate with all the necessary systems and coordinate the platooning functions. This can be visualized through the diagram below.

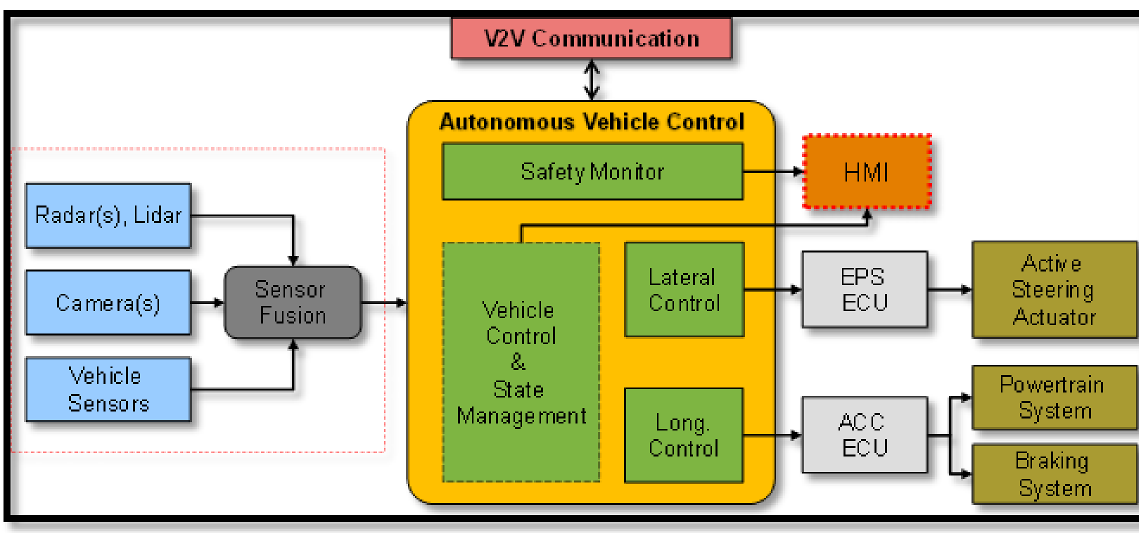


Figure 1: Platooning Function block diagram

2.2. System Definition

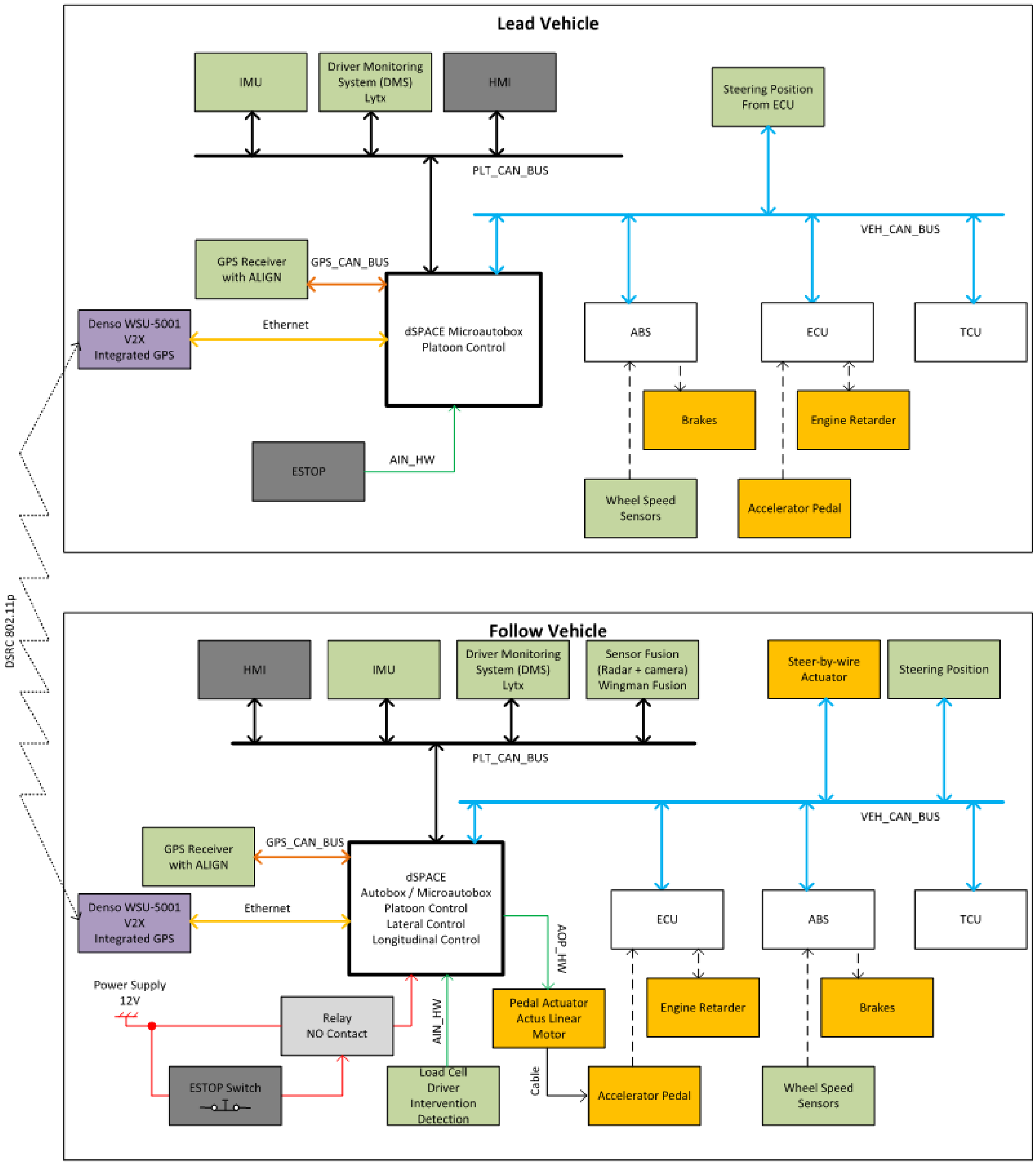


Figure 2: Lead and Follow vehicle system Block Diagrams

The platooning system is made up of two vehicles fitted with a series of actuator and sensor systems in addition to a Platooning Control Module on each vehicle. The LV Platooning Control Module will process data related to the vehicles current state including position from the GPS, acceleration and rotation rate from an IMU and driver demand such as accelerator pedal, brake pedal and steering information. This data will be used in logic to manage the overall logistical and safety strategy of the platoon as well as be transferred through a DSRC to the follow vehicle for use in motion control. This is laid out in the above block diagram.

Using the data transmitted from the LV, local vehicle information and onboard sensing systems, the FV Platooning Control Module will determine the necessary actuator commands to meet the platooning demands determined by the overall platooning strategy and any applicable safety concerns. In doing so, it is necessary to characterize the current state of the both vehicles and project a planned path to control the vehicle. The sensing systems include the Wingman Fusion camera and radar driver assistance system, Lytx driver monitoring system, NovAtel differential GPS and an IMU unit.

3. VEHICLE TECHNICAL SPECIFICATIONS

The purpose of the Vehicle Technical Specifications (VTS) is to lay out the high-level vehicle specification of the base vehicle, the communication interface, and vehicle stability and safety monitoring.

The VTS does not discuss software algorithms, detailed component specifications or system interfaces; these are discussed in the SSTS.

3.1. Base Vehicle

The base vehicles to be used are International ProStar+ supplied by Navistar hooked up to a 53 ft. Box trailer. Both trucks include a MaxxForce 13 engine and an Eaton UltraShift + Transmission and are fitted with Bendix ABS, Traction Control, and Stability control. The full vehicle specification can be seen in Appendix 1.

3.2. Communication Interface

The intra-vehicle communication will be based on CAN wherever possible and logical. The inter-vehicle communication will be through DSRC.

3.2.1. Platooning Network - CAN 1

CAN 1 on each vehicle is reserved for communication between the PCM and the additional sensor systems fitted on the vehicles.

The Platooning Control Modules and the additional sensor systems shall communicate via the Controller Area Network (CAN) version 2.0 protocol.

The CAN interface shall operate at a bus speed of 500 kbps.

All messages shall use the standard 11-bit CAN identifier.

3.2.2. Vehicle Network - CAN 2

CAN 2 on the ECU is reserved for communication with the in-vehicle CAN network to enable 2-way communication with the in-vehicle control modules

The CAN interface shall operate at a bus speed of 250 kbps.

All messages shall use the extended 29-bit CAN identifier.

3.2.3. GPS Network - CAN 3

CAN 3 on the ECU is reserved for communication with the GPS controller to receive the instantaneous latitude, longitude and heading information of the respective vehicles.

The CAN interface shall operate at a bus speed of 500 kbps.

All messages shall use the extended 29-bit CAN identifier.

3.2.4. Inter-Vehicle Network – DSRC

Each PCM will communicate over Ethernet to the Denso WSU-5001 unit. The information necessary for the other vehicle will be sent to the local DSRC unit and received by the other vehicles DSRC unit.

3.2.5. Calibration and Data logging

The calibration and data logging of the platooning software shall be done using the dSpace proprietary ControlDesk software.

3.3. Safety and Vehicle Stability

The vehicle shall have provisions to ensure that safety and vehicle stability will be maintained at all times. This shall be done by having logic to predict the future trajectory of the FV based on the LV's path, driver warnings through the HMI, road hazard detection and autonomous system fault detection.

3.3.1. Rollover Protection

There shall exist logic to ensure the vehicle velocity does not increase above the safe limit for a given steering wheel angle to ensure we do not approach the rollover limit. This may be done using a table for maximum steering wheel angle and velocity combinations and predicting expected trajectory of the vehicles.

3.3.2. Safety Monitoring

Logic shall exist that ensures the platoon vehicles are being operated and maintaining safe distances from each other, and that desired trajectories are not exceeding specified longitudinal and lateral limits of the platoon and the vehicles within the platoon.

This may be done by using inputs from GPS, cameras, sensors, IMU and by predicting the future trajectory of the FV based on the trajectory taken by the LV. In the event that the logic detects a potential unsafe trajectory or maneuvers, the vehicle drivers will be informed via the HMI. This may be done by monitoring the longitudinal distance between the vehicles as well as the deviation of the FV path with respect to the LV path or by just enabling the driver intervention or emergency button press.

3.3.3. Fault Detection

At all times fault detection logic will be running in the background. As a fault is detected in a vehicle sub-system these will be relayed to the drivers both audibly and visually through the HMI by means of a display and/or speakers. Faults will also be classified based on their severity. The autonomous driving mode shall be disabled in the presence of any faults for safety reasons.

An example could be, the driver of the FV when in autonomous platooning should be warned of a brief loss of V2V communication. However, if V2V communication is completely lost the driver of the FV shall be told to override the autonomous system and take full manual control of the vehicle.

3.3.4. Safety and Hazard Identification

Logic shall exist to identify system hazards and actions that shall be taken to mitigate those hazards.

A safety and hazard analysis has been performed to understand potential hazard and safety issues that may occur during truck platooning. The analysis also discusses potential safety goals and how hazards can be mitigated. The actions identified to mitigate specific hazards and safety concerns shall be populated into the logic.

Refer to document RD15 -001743-1 for the output of the preliminary safety analysis

3.4. Truck Platooning Demonstration

The truck platooning system discussed in this document will be demonstrated as defined is the Platooning demonstration specification RD15-001733-01.

3.5. Truck Platooning Operational Requirements

The operational requirements that the truck platooning system has to meet are laid out in the Operational Requirements Document RD 15/001716.1.

In this document requirements such as lateral and longitudinal accelerations during maneuvers, following gaps, HMI, platooning modes, etc. are discussed.

4. SUBSYSTEM TECHNICAL SPECIFICATIONS

The purpose of the Subsystem Technical Specifications (SSTS) is to describe the specification of the major components fitted to the base vehicle, the communication interface, vehicle stability and safety monitoring.

4.1. Electronic Control Unit (ECU)

The electronic control unit (ECU) installed in each vehicle for platooning shall be capable of interfacing data from the vehicle through CAN and I/O and communicate this data to the other vehicle through DSRC.

4.1.1. Lead Vehicle Interface Specification

The ECU installed on the LV will have the ability to communicate with the vehicle subsystems. This section serves to expound the means of this communication and in doing so gives a brief overview of each system. More detailed information can be found in the Individual System Specification section of this document or the systems specification sheet.

4.1.1.1. DSRC

The lead vehicle shall communicate to the follow vehicle using DSRC communication.

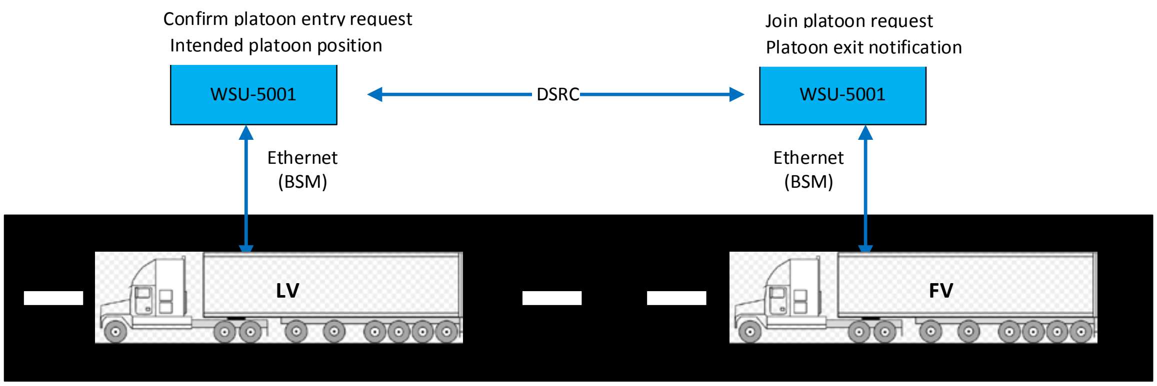


Figure 3: DSRC communication

Denso WSU-5001 shall be considered for DSRC communication which supports Ethernet and CAN interface. GPS is integrated with this module and capable of sending Basic Safety Messages (BSM) as well as a-la-carte messages.

The relevant messages for platooning communication shall be defined as an ala-carte message in order to include all the messages from the HMI as well as the important messages from either vehicle. A potential set of messages that are transferred over the DSRC are specified in later sections of this document.

The below diagram shows the architecture of WSU-5001

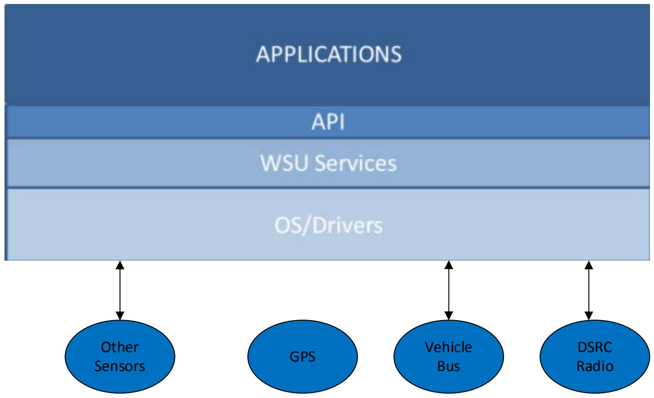


Figure 4: DSRC API interface

4.1.1.2. IMU

Inertial Measurement Unit (rate and acceleration sensor) shall provide Yaw, Roll and Pitch through CAN message to the control unit.

Accelerometers X, Y, and Z values shall be received from IMU module thought CAN messages.

4.1.1.3. GPS

FlexPak6 shall be used for GPS interface and communicate to ECU through the CAN bus.

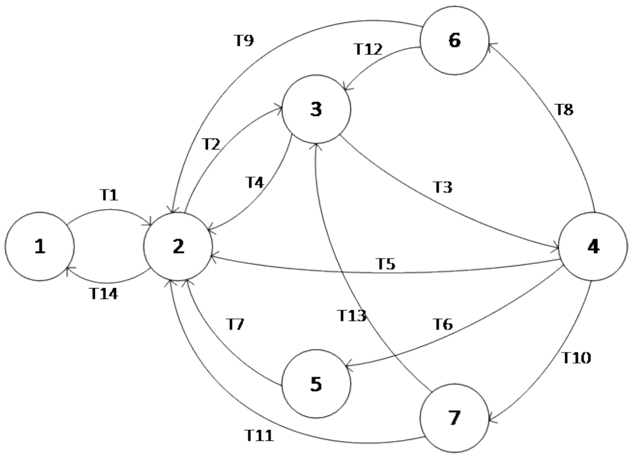
4.1.1.4. HMI

HMI shall have the capability to provide an interface to the driver for LV and FV to communicate through CAN message and DSRC messages.

The HMI screen will display most appropriate information based on the operating mode of the platoon manager. Following is the summary of the HMI design interface.

Mode #	Mode	LV		FV	
		LV- Signals	HMI - Controls	FV- Signals	Controls
Mode 1	Platoon disabled	GPS status V2V status Platooning Mode	Platoon disabled	GPS status V2V status	Platoon - Disabled GPS status V2V status
Mode 2	Standby	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - standby	Distance to LV Delta velocity wrt LV	Platoon - Standby Following distance - Enabled Delta velocity - Enabled Join platoon Request - Enabled
Mode 3	Joining Platoon	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - Join active Accept - Enabled Denied - Enabled	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - Join Active Join platoon Request - Disabled Following distance - Enabled Delta velocity - Enabled
Mode 4	Full Platoon Active	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - Active Platoon leave request - Enabled	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - Active Follow distance (Slider) Platoon leave request - Enabled
Mode 5	Leaving / Dissolving Platoon	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - Leave Active	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - Leave Active
Mode 8	Error / E-Stop active	Distance to LV Delta velocity wrt LV Platooning Mode	Platton - Error	Distance to LV Delta velocity wrt LV Platooning Mode	Platoon - Error

Platoon State Manager



States:	
1	Manual platoon disabled
2	Stand by
3	Join request active
4	Platoon full autonomous mode
5	Leave request active
6	Longitudinal Feedback control active
7	Lateral Feedback control active

Transition conditions			
T1	C1 AND C2	**C1**	No system errors
		C2	Good tracking / localization (confident range, range_rate)
T2	C3	**C3**	LV Driver accepts FV Request to Join
T3	C4 AND C5	**C4**	min < join dist < max for time > cal
		C5	min < join deltaVel < max for time > cal
T4	C6	**C6**	[C4 AND C5 == 0] for time > cal OR C7
T5	C7	**C7**	Emergency leave [C1 AND C2 == 0]
T6	C8 OR C9	**C8**	Request to leave LV (HMI)
		C9	Warnings based controlled driver takeover
T7	C10 OR C11	**C10**	range > leave distance
		C11	FV Drv accepts leave req started from LV or Warnings
T8	C12 OR C13	**C12**	Manual takeover of lateral control
		C13	Lateral control error
T9	C14 OR C15	**C14**	Manual takeover of longitudinal control
		C15	Longitudinal control error
T10	C14 OR C15	**T9**	[C13 OR C14 == 1]
T11	C12 OR C13	**T8**	[C11 OR C12 == 1]
T12	C16 OR C17	**C16**	Longitudinal control enable from HMI
		C17	Longitudinal manual takeover stop detected
T13	C18 OR C19	**C18**	Lateral control request active from HMI
		C19	Lateral manual takeover stop detected
T14	C1 AND C2	**T5**	[C1 AND C2 == 1]

4.1.1.5. *Vehicle Interface*

Vital Vehicle signals like Steering angle, Brake pressure, Accelerator pedal position, wheel speed, etc., shall be communicated to ECU through CAN messages from the vehicle ECU.

4.1.1.6. *DMS*

Driver management system shall be capable of monitoring driver activities through sensors and communicate to ECU through CAN messages.

4.1.2. Follow Vehicle Interface Specification

FV vehicle shall have the similar capability to the LV including DSRC, HMI, IMU and vehicle interface. Additional systems installed solely on the FV are included in this section

4.1.2.1. *Bendix Wingman Fusion*

Sensor fusion shall use the sensor interface to detect the obstacles and road conditions and communicated to the ECU through CAN messages.

4.1.2.2. *Throttle Control*

An Actus linear actuator will be used to actuate the accelerator pedal while in platooning mode. The actuator has a dedicated controller that can be controlled to any position continuously through DAC output from ECU.

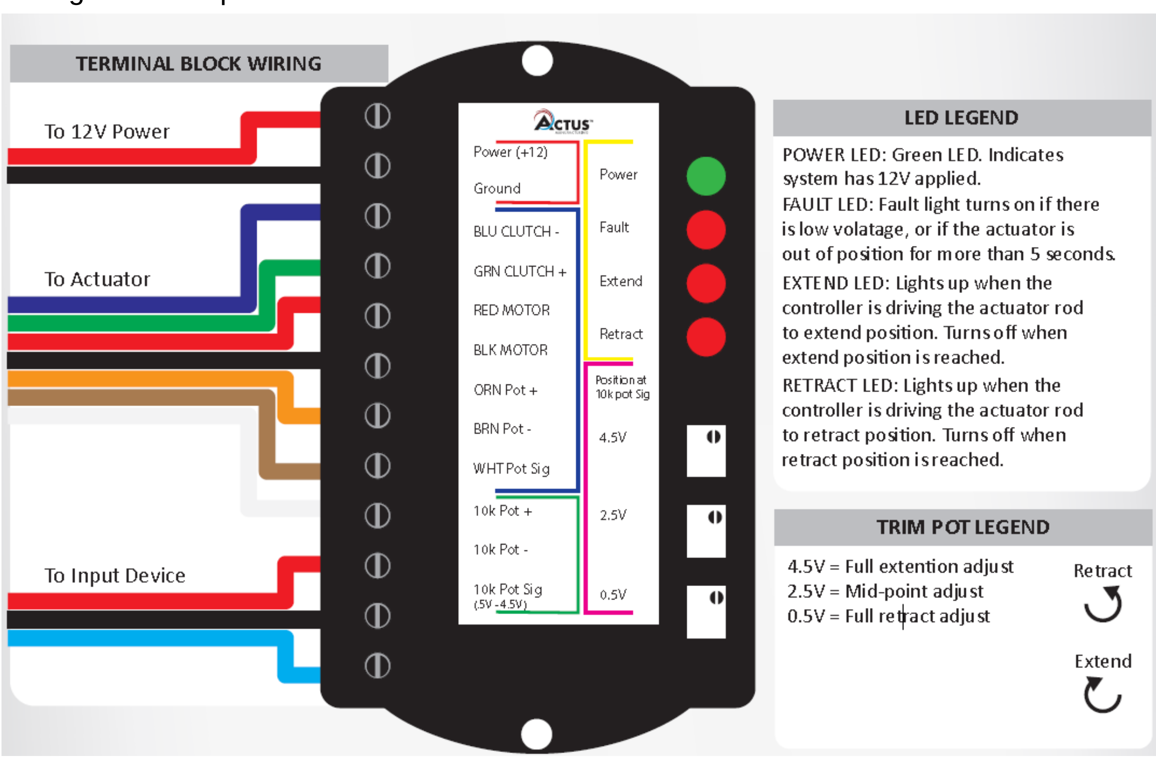


Figure 5: Throttle control interface

4.1.2.3. Accelerator Pedal Load Cell

To determine when the driver is overriding the acceleration request while in platooning mode, a load sensor will be used on the pedal. This will communicate to the ECU via a hardwired connection.

The load sensor hardware interface shall be determined in the electrical schematic diagram.

4.1.3. Battery

The vehicle battery (12V) shall be connected to a continuous 10A fuse and connected to the ECU. ECU shall be capable of full operation with an input voltage between 9V to 16V DC voltage range.

Pin details for the power supply circuit shall be determined in the electrical schematic diagram of the subsystem.

4.1.4. Ignition

Ignition switch signal is connected to ECU enable pin to prevent the battery discharge of the battery when the car engine is not running.

4.1.5. Emergency Stop

The ignition wire shall have an emergency stop switch between the ECU input and the output of the relay. This switch will be normally closed. The driver can press the emergency stop switch to power down the controller and return to full manual control of the vehicle.

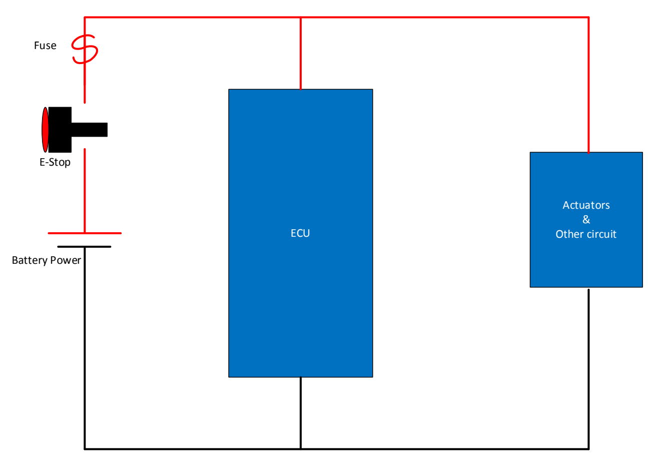


Figure 6: Emergency stop diagram

4.1.6. Driver Power

The driver power for the actuators and controllers shall be determined by the power supply requirements and circuit.

4.1.7. Driver Ground

Driver ground shall provide a grounding point for ECU. The three terminals will be connected to the chassis ground on the vehicle.

4.2. HMI Device

Interaction between the operators of each vehicle and the platooning control system will be handled through an HMI device. This may be a touchscreen device mounted on the dash and will function as the control gateway to the platooning system. Joining, leaving and modifying the platoon may be done so through this device. Additionally, system information such as fault warnings, platooning status, following distance, etc. may be conveyed to the driver.

HMI shall be capable of communicating through CAN.

4.3. Platooning

The motion controller's main purpose is to utilize the steering, braking, and throttle actuators to direct safely the vehicle along the intended path designated by the platooning control system. This can be accomplished using some different methods that will be tuned for accuracy and for stability at different velocities and roads based on the demonstration.

The platooning system may function in the manner laid out in the following subsections. For this phase of the project, the platoon will in all situations be limited to a maximum of one LV and one FV.

4.3.1. Join Platoon

Under suitable conditions, a vehicle may join a platoon made up of at a minimum a designated LV with a trained platooning driver in a state of accepting requests to join the platoon. The process to join a platoon involves the interaction of the LV operator and the FV operator through the HMI device and may be characterized by the following procedure:

1. The ECU on FV performs a health check of primary platoon relevant signals to determine if the vehicle may join the platoon
    a. This request is accepted by the platooning control system if all criteria are met
2. The operator of the FV indicates a desire to join the platoon and maintains a safe relative speed and distance to the LV.
3. The operator of the LV accepts the request, and the platoon is formed if all criteria are met for both vehicles.

4.3.2. Leave Platoon under Normal Operation

While the platoon is underway, the LV and FV operators will be able to request the FV to leave the platoon in a controlled manner. Once the leave request is initiated from FV or LV, the system will initiate a dissolve platoon request. The following procedure may characterize the procedure:

1. A request is made by either the FV or LV
2. The FV gradually increases the following distance to the LV to a specified safe distance and the follow vehicle is notified to take control

3. The control of the FV is ceded to the operator once the specified distance and speed criteria are met

4.3.3. Leave Platoon under Emergency Condition

If the LV presses the E-stop owing to loss of communication with vital systems or some other emergency situation the platoon shall be disbanded immediately and both operators shall be alerted.

4.3.4. Driver Override

The FV operator will be able to override the steering actuator, accelerator pedal actuator, and the braking command. The platooning system may continue to exert forces or torques on the actuators and the drivers will need to provide additional input to overcome these actuators. Full manual mode of the control system may not be ceded immediately upon override of a single system depending on the current state of the platoon and vehicle.

4.3.5. Motion Controller

The motion controller of the FV will reside on the FVPCM and will handle controlling the vehicle while in any platooning related maneuvers. It will be made up of an observer to determine the vehicle, subsystem and environmental status, a longitudinal controller, and a lateral controller. The control model will be created in Simulink and Matlab.

4.4. Individual System Specification

The individual systems involved in the platooning control of the vehicle are described in more detail in this section. Where available, CAN messages are provided. Full detail of the CAN interface will either be updated in this document or included in another CAN Interface Control Document once it has been developed. For more information about the particular systems refer to the documentation provided by the supplier.

4.4.1. Bendix Wingman Fusion

Information from the Bendix driver assistance system Wingman Fusion will be used in the estimation of vehicle to vehicle distance and relative location. This system is installed on the FV and will be transmitted to the FVPCM over the platooning CAN network.

Bendix Wingman fusion can track up to 10 objects with a camera and a radar system. Each system will have a set of CAN messages containing the available information. For further information refer to the Bendix documentation.

4.4.1.1. RADAR CAN Message Definitions

The following CAN signals make up the overall RADAR system status (units mentioned in brackets):

Signal	Units
status_multiplexor	

number_of_tracks	
actual_vehicle_speed	m/s
vehicle_reference_acceleration	m/s^2

The number_of_tracks define the total number of tracks detected by the RADAR. For each track object, the following information is transmitted over CAN:

Signal	Units
acceleration_over_ground	m/s^2
asso_video_ID	
corrected_lateral_distance	m
is_video_associated	
lateral_position	m
radar_confidence	
Range	m
relative_velocity	m/s
track_selection_status	
uncorrected_angle	deg
video_confidence	

4.4.1.2. Video CAN Message Definitions

For each object detected by the camera, the following information is transmitted over CAN:

Signal	Units
Id	
longitudinal_distance	m
relative_velocity	m/s
tan_left_angle	
Class	
tan_right_angle	
message_counter	
Lane	

4.4.2. Denso DSRC/GPS

The inter-vehicle communication will be handled by a Denso WSU-5001 DSRC unit.

4.4.2.1. DSRC Message Definitions

The DSRC messages are defined between the LV and FV. The potential signal set that can be transferred over the WSU unit is listed below:

The list of signals that are transmitted from FV to LV shall include the following:

Signal	Units
Platoon Join Request	
Platoon Leave Notify	

Platoon Mode of FV	
Following Distance	m
Message Roll Count (for debugging)	

The list of signals that are transmitted from LV to FV shall include the following:

Signal	Units
Latitude of LV	deg
Longitude of LV	deg
Instantaneous yaw rate of LV	rad/s
Course Over Ground of LV	rad
Platoon Join Accept	
Platoon Leave Request	
Platoon Mode of LV	
Follow Distance Target	m
Vehicle Speed of LV	m/s
Acceleration of LV	m/s^2
Steering Wheel Angle of LV	cnt
Brake Pedal Position of LV	pct
Accelerator Pedal Position of LV	pct
Message Roll Count (for debugging)	

4.4.2.2. Accuracy

In testing performed by DENSO, worst-case WSU-5001 GPS accuracy was measured to be +/- 2.5m, with these cases occurring at speeds lower than 15 mph. Average WSU-5001 GPS accuracy during testing was +/- 1.03m.

4.4.2.3. Status Monitoring

The LVPCM shall transmit a heartbeat sequence counter to the FVPCM. The counter is a 8-bit value between 0 and 255, which increments by one for each successive message transmitted. Following a value of 255, the counter rolls over to 0. The FVPCM shall monitor the counter and detect if the counter is not incrementing by one. If the FVPCM detects this behavior, it shall set the LVPCM CAN data heartbeat fault.

If LVPCM CAN data heartbeat fault is currently set, and the FVPCM receives *cic_num_heartbeatFaultRcvry* consecutive heartbeat sequence counters that increment successively by one, the FVPCM shall clear the LVPCM CAN data heartbeat fault.

A CAN message transmitted by LVPCM to be received by the FVPCM may include a rolling count. The rolling count is a 8-bit value between 0 and 255, which increments by one for each successive message transmitted. Following a value of 255, the counter rolls over to 0. The FVPCM shall monitor the count and detect if the counter is not incrementing by one. If the FVPCM detects this behavior, it shall initiate the corresponding fault handling procedures.

If the FVPCM has not received any CAN message from LVPCM within *cic_tm_timeoutLVPCM_ms*, the FVPCM shall set LVPCM CAN Data Timeout flag.

If LVPCM has not received any CAN message from the FVPCM within *cic_tm_timeoutFVPCM_ms*, LVPCM shall set the FVPCM CAN Data Timeout flag.

4.4.3. TRW EPAS Steering

The steering actuator command from the motion controller shall be a requested steering wheel angle with positive indicating left-hand turning.

The brake and throttle commands shall be mutually exclusive and be a requested value from 0-1.

4.4.4. NovAtel GPS

To increase the accuracy of the GPS coordinate estimation, a NovAtel FLEX6-G2S-Y0G-TTN will be installed in each vehicle with a GPS-702-GG antenna. Additionally, the NovAtel ALIGN firmware will be utilized to increase differential accuracy between the two receivers in each vehicle.

4.4.5. Align

ALIGN firmware combines two or more receivers to generate precise positioning and heading for dynamic application. ALIGN uses GPS, GLONASS and SBAS to provide high solution accuracy and availability, even in difficult environments. Accuracy from synchronized solutions is provided with output rates up to 20 Hz.

4.4.6. Throttle Actuator

The throttle request from the platooning control system will be carried out by an Actus linear actuator connected to the accelerator pedal. The actuator would have the ability to modulate the accelerator pedal when requested by the platooning control system while still allowing control to the driver when the power is cut through the E-stop. The platooning control system can also cede control to the driver whenever necessary such as when the driver applies pressure to the pedal.

4.4.7. Navistar Engine

Control of the engine will most likely be handled through the throttle actuator while engine retarder will be handled through the Bendix Wingman Fusion system.

4.4.8. HMI

The HMI device will be connected to the ECU through CAN in order to react to the driver inputs as well as keeping the driver informed of the current platooning state and all the relevant information that is of interest in the current platooning state.

The following table lists out the potential signals that are communicated between the EVU and the HMI on the LV.

Signal	Units	Notes
Platoon Join Accept LV		HMI Transmit
Platoon Leave Request LV		HMI Transmit
Follow Distance Target LV	m	HMI Transmit
Platoon Enable LV		HMI Receive
Platoon Join Request LV		HMI Receive
Estop Active LV		HMI Receive
Platoon Mode LV		HMI Receive

The following table lists out the potential signals that are communicated between the EVU and the HMI on the FV.

Signal	Units	Notes
Platoon Join Request FV		HMI Transmit
Platoon Leave Request FV		HMI Transmit
Follow Distance Target FV	m	HMI Transmit
Platoon Enable FV		HMI Receive
Platoon Join Accept FV		HMI Receive
Platoon Mode FV		HMI Receive

5. APPENDIX

Appendix 1. International Pro Star Truck Specifications.

	Vehicle 1	Vehicle 2
Make	International	International
Model	ProStar +	ProStar +
Model Year	2013	2013
Build Date	20JAN12	13FEB12
Current Mileage	241,709	263,162
VIN	3HSDJSJR7DN157097	3HSDJSJR5DN157115
Chassis Number	DN157097	DN157115
Configuration		
Cab	73" Sleeper Hi-Rise	73" Sleeper Hi-Rise
Chassis	6 X 4	6 X 4
Wheelbase	228"	228"
BBC	122"	122"
AF	53"	53"
GVWR	52,000lbs	52,000lbs
Front Axle		
Make	MFS-12-143A	MFS-12-143A
Rating	12,000lbs	12,000lbs
Rear Axles		
Make	MT-40-14X-3CFR	MT-40-14X-3CFR
Rating	40,000lbs	40,000lbs
Engine		
Type	MaxxForce 13	MaxxForce 13
ESN	125HM2Y4142704	125HM2Y4145119
Power	450HP	450HP
Torque	1550/1700ft-lbs	1550/1700ft-lbs
Gov Speed	1900rpm	1900rpm
Transmission		
Make	Eaton UltraShift +	Eaton UltraShift +
Model	FOM-15E310C-LAS	FOM-15E310C-LAS
Gears	10-speed	10-speed
Brakes		
Brake Control	Bendix ABS/Traction Control/Stability Control	Bendix ABS/Traction Control/Stability Control
Front Brakes		
Chambers	Haldex	Haldex
Foundation	Meritor Q-Plus	Meritor Q-Plus
Rear Brakes		
Chambers	Haldex	Haldex
Foundation	Meritor Q-Plus	Meritor Q-Plus

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TABLE OF CONTENTS

Version 4.1

1. INTRODUCTION

1.1. Revision History

Revision ID	Date	Issued by	Purpose
1.0	28 Aug 15	CKI	Initial release
2.0	30 Nov 15	MDM	Response to Mo's comments
3.0	20 Jan 16	MDM	Response to Mo's comments
4.0	21 Jul 16	LEB1	Final cleanup Requirements renumbered Qualification matrix removed and replaced with separate, external verification matrix spreadsheet
4.1	8 Aug 16	LEB1	

1.2. Purpose

The purpose of this document is to lay out the operational and functional requirements for a two vehicle truck platooning demonstration for Texas Department of Transportation (TxDOT) and lead by Texas A&M Transportation Institute (TTI). The project's objective is to validate the feasibility and benefit of truck platooning. For this project, two Class 8 tractor trucks with trailers will be used. The first vehicle, the platoon Lead Vehicle (LV), is driven manually by a trained driver. The second vehicle, the Follow Vehicle (FV), has a driver but can be autonomously controlled to follow the path of the LV at a specified distance.

In initial releases, the document may form a working base to clarify requirements. As the requirements capture progresses, the document will be further validated and at completion will describe the initial implementation of the platooning system. This is a living document and will be updated, as required, during the development and implementation of the platooning system.

Each paragraph in this document is categorized as follows:

- **For Information** – These paragraphs provide information only and are not, requirements, assumptions or limitations. NOTE: Paragraphs without an explicitly stated category (of which this paragraph is an example) are to be regarded as For Information.
- **Requirement** – These paragraphs describe required functionality. Where appropriate further information that is not itself a requirement is appended to the paragraph in *italics*.
- **Limitation** – These paragraphs document known limitations of the functionality as described or which will be acceptable in the implementation. Before implementation begins these limitations should be reviewed carefully, because changing or deleting the limitations may have a significant impact on the implementation.

- **Assumption** – These paragraphs document assumptions about the required functionality, development process or components external to the Control System.
- **Definition** – These paragraphs define terminology used elsewhere in the document.

1.3. Scope

The scope of the requirements laid out in this document only refer to the operational and functional requirements of a platooning system for the purpose of a proof of concept demonstration. They do not define system and vehicle architectures, component specifications or the implementation of software and its algorithms.

This specification may contain explanatory or exemplary items (text, figures, etc.) outside the requirements specification. These explanatory and exemplary items are not part of the specification.

1.4. Audience

Audience will be defined as the participants in evaluation and observation of the development and the delivery.

1.5. Definition of Terms / Abbreviations

1.5.1. Levels of Obligation

Use of the words "shall", "should", "must", "will", and "may" within this Specification observe the following rules:

“Shall”	The word *SHALL* in the text expresses a mandatory requirement of the Specification.
“Should”	The word *SHOULD* in the text expresses a recommendation or advice on implementing such a requirement of the Specification, such recommendations or advice are expected to be followed unless good reasons are stated for not doing so.
“Will”	The word *WILL* in the text expresses a requirement on the usage of the tool
“May”	The word *MAY* in the text expresses a permissible practice or action. It does not express a requirement of the Specification.

1.5.2. General

Term	Description
DSRC	Dedicated Short Range Communications
FHWA	Federal Highway Administration
FV	Following Vehicle
HMI	Human-Machine Interface
IEEE	Institute of Electrical & Electronics Engineers
LV	Lead Vehicle
SRS	Software Requirement Specification
TTI	Texas A&M Transportation Institute
TxDoT	Texas Department of Transportation
V2V	Vehicle to Vehicle
VCRM	Verification Cross Reference Matrix

1.6. References

In the event of a conflict between this document and the reference documents, this document shall take precedence.

ID	Document Source	Date / Revision
RD 15/001733.1	TTI Truck Platooning Demonstration Plan	1.0
IEEE 802.11p	Telecommunications & Information Exchange Between Systems part 11	2010
FHWA-JPO-12-021	Vehicle Information Exchange Needs for Mobility Applications Version 2.	2012

1.7. Requirement Format

A requirement defined within this document shall follow the format below:

[REQUIREMENT_PROTOTYPE]

ID: [REQ_ID]

Parents: root
Classification: For Information, &Requirement, Limitation, Assumption, Definition
[Requirement End]

[/REQUIREMENT_PROTOTYPE]

NOTE: [REQ_ID] represents a unique requirement ID.

1.8. Document Information (for Automation)

File Location	Specification Documents
Req. Prefix	SRS_
Review File	
Type of Document	Requirement Specification

2. OPERATIONAL REQUIREMENTS

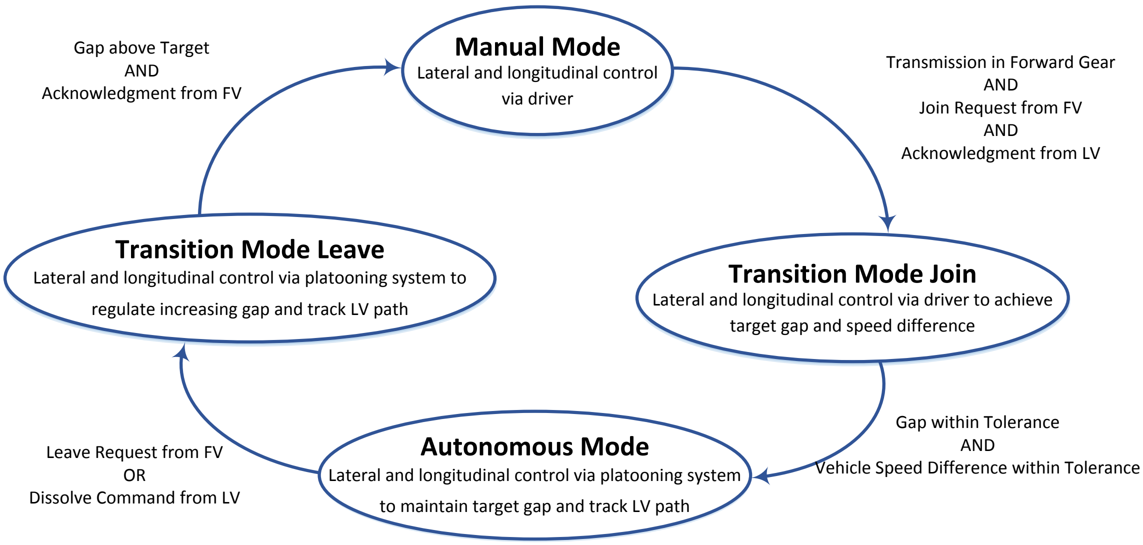
2.1. Platooning Terminology

This section describes terms used in the context of platooning operation, including modes and transitions between modes.

Term	Description
Autonomous Platooniing Mode	Operation in which the FV's steering, braking and accelerator are nominally under the control of the platooning system and are being used to control one or more of FV speed, gap between the FV and LV and the driving path of the FV. Each of the actuators for these systems are designed so that they can be overridden by inputs from the FV's driver, so that the FV's driver has ultimate authority over the vehicle's operation and safety.
Manual Mode	Operation in which each vehicle is under full control of its driver. The autonomous system actuators have no direct or indirect control over the vehicles' steering, braking, engine or transmission systems
Transitional Mode-Join	Operation in which the system is transitioning from Manual Mode to Autonomous Platooning Mode
Transitional Mode-Leave	Operation in which the system is transitioning from Autonomous Platooning Mode to Manual Mode

2.2. Operational Modes, Transition Conditions and Related Requirements

When operating the platooning system, several different modes are provided as described in following subsections. These include a Manual Mode, Autonomous Platooning Mode and Transitional Modes that are active when changing between manual and autonomous operation. The requirements when operating in these modes and the conditions under which transitions occur between these operating modes are described in these requirements in Section 2.2. An overview of the relationship between the various operating modes and transitions can be visualized in the form of the state transition diagram shown in the figure that follows. However, note that this figure is provided for clarification and is not part of the formal requirements. The requirements text takes precedence in the event of any conflicts between the figure and the written requirements.



Overview of Operating Modes and Transition Conditions

2.2.1. Human-Machine Interface (HMI)

The system includes human-machine interfaces (HMIs), i.e., interactive displays, in each vehicle in the platoon. The purpose of these HMIs is to provide key information to the drivers that is relevant to the operating mode, as well as to allow a mechanism for providing inputs to the system when required. The main requirements for the HMI are listed in this section and reflect a goal to have only limited information displayed on the HMI so as to minimize driver distraction. Other operating mode-specific requirements for the HMI are listed in sections relevant to the operating mode or the associated transitions.

ID: SRS_001

The HMI display should be specific to the current operating mode, uniquely identify the operating mode and include the key information or inputs needed by the driver for that mode.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_002

The LV and FV shall have the means to visually inform the driver of system warnings.

Parents: root
Classification: Requirement
[Requirement End]

2.2.2. Manual Mode Operation

When operating in Manual Mode, it is expected that the LV and FV shall be able to be driven by their operators with no loss of vehicle function or performance relative to a baseline vehicle of the same type that is not modified to support platooning operation.

ID: SRS_003

When operating in Manual Mode, the system shall not control or influence the operation of the vehicle's steering, accelerator or brake. The vehicles shall remain under full control of their respective drivers.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_004

The system shall not transition out of Manual Mode if either vehicle is in reverse gear.

Parents: root
Classification: Limitation
[Requirement End]

The drivers should be instructed of this limitation to avoid platooning in reverse, though no active strategy to prevent this obvious limitation is part of the concept demonstration.

ID: SRS_005

When operating in Manual Mode, the FV driver shall have a means to request via the HMI to join the Platoon.

Parents: SRS_001
Classification: Requirement
[Requirement End]

ID: SRS_006

The FV driver should not be requested to join the platoon via the HMI under any condition that potentially impedes the capability of the system to successfully join / maintain the platoon.

Parents: SRS_001
Classification: Limitation
[Requirement End]

For the concept demonstrator on nonpublic roads, there are operating conditions under which the platoon is not expected to be demonstrated. These are captured in Section 2.4. In addition, the drivers should be instructed that other conditions may impede the system from engaging in autonomous operation. The two main examples expected would be a nonfunctional DSRC connection between the vehicles or a lack of a valid GPS signal.

ID: SRS_007

When operating in Manual Mode, the LV driver shall have a means to acknowledge or reject a request via the HMI from the FV driver to join the Platoon

Parents: SRS_001
Classification: Requirement
[Requirement End]

2.2.3. Transitional Mode Operation

Transitional modes describe the operating modes in which the system is in the process of changing between Manual Mode and Autonomous Platooning Mode. There may be several sub-modes associated with these transitional modes in the implementation of the system in software, though from an operator's point of view, these sub-modes are transparent and are not described in this document.

ID: SRS_008

The system shall provide two transitional modes:

- Transitional Mode-Join shall be the operating mode when the system is in the process of changing from Manual Mode to Autonomous Platooning Mode
- Transitional Mode-Leave shall be the operating mode when the system is in the process of changing from Autonomous Platooning

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_009

When operating in Transitional Mode-Join, the system shall not control or influence the operation of the vehicle's steering, accelerator or brake. The vehicles shall remain under full control of their respective drivers.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_010

When operating in Transitional Mode-Join, the system shall compute and display the gap between vehicles and relative vehicle speed of the FV on the HMI.

Parents: root
Classification: Requirement
[Requirement End]

The purpose for displaying the gap and vehicle speed in Transitional Mode-Join is to provide feedback to the FV driver, who will need to match a gap target and LV speed within a set tolerance to complete the transition into Autonomous Platooning Mode.

ID: SRS_011

When operating in Transitional Mode-Join, the system reverts back to Manual Mode if the FV driver cannot get the FV within the desired gap and speed window in 60 seconds after the join request was accepted by the LV driver

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_012

When operating in Transitional Mode-Leave, the system shall provide control of the FV's steering, braking and accelerator to maintain a desired gap between the FV and LV and the lateral position of the FV with respect to the LV's path.

Parents: root

Classification: Requirement
[Requirement End]

ID: SRS_013
When operating in Transitional Mode-Leave, the system shall increase the gap target at a rate of 1 m/s to a maximum of 30 m.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_014
When operating in Transitional Mode-Leave, the HMI in the FV shall display the actual gap between vehicles.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_015
When operating in Transitional Mode-Leave and the actual gap achieves the maximum 30 m target within ±0.5 m, the system shall provide a means for the FV driver to confirm the completion of the leave process via the HMI.

Parents: root
Classification: Requirement
[Requirement End]

The aim of having the driver confirm completion of the leave process is to ensure that the driver is attentive when the vehicle is transitioning from autonomous back to manual operation. This final transition occurs after the gap has been increased to 30 m for safety.

ID: SRS_016
During both the Transition Mode-Join and Transition Mode-Leave events, the lytx DriverCam system may be enabled for driver monitoring and training purposes

Parents: root
Classification: For Information
[Requirement End]

2.2.4. Autonomous Platooning Mode Operation

ID: SRS_017
When operating in Autonomous Platooning Mode, the system shall provide control of the FV's steering, braking and accelerator to maintain a desired gap between the FV and LV and the lateral position of the FV with respect to the LV's path.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_018
When operating in Autonomous Platooning Mode, the FV driver shall be allowed to request a change in the platoon following gap via the HMI.

Parents: SRS_001, SRS_017
Classification: Requirement
[Requirement End]

ID: SRS_019

When operating in Autonomous Platooning Mode, the system shall allow the FV to LV distance (gap) target to be within the range from 10 m to 70 m.

Parents: SRS_017
Classification: Requirement
[Requirement End]

ID: SRS_020

When operating in Autonomous Platooning Mode, when a gap change is requested between the LV and FV, the gap shall adjust at a velocity not greater than 5 m/s.

Parents: SRS_017
Classification: Requirement
[Requirement End]

ID: SRS_021

When operating in Autonomous Platooning Mode, the FV should track the path taken by the LV.

Parents: root
Classification: Requirement
[Requirement End]

For this demonstration program, the development settings for FV to LV gap in the Autonomous Platooning Mode will typically be set from 10 m to 25 m, based on the provided trailer lengths (15 m) and unladen operating conditions. Performance limits will not be factored into functional concept verification development.

ID: SRS_022

When operating in Autonomous Platooning Mode, the front of FV shall maintain a distance to the rear of the LV within a tolerance of +/- 0.5 meters of the requested following gap at steady state.

Parents: SRS_017
Classification: Requirement
[Requirement End]

ID: SRS_023

When operating in Autonomous Platooning Mode, the centerline of the FV shall follow the centerline of the LV within a tolerance of +/- 0.5 meters in a straight line, assuming no added inaccuracies are introduced from the sensors.

Parents: SRS_017
Classification: Requirement
[Requirement End]

ID: SRS_024

The LV shall not have autonomous driving capability.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_025

When operating in Autonomous Platooning Mode, the LV shall have a means to request via the HMI to dissolve the platoon.

Parents: SRS_001
Classification: Requirement
[Requirement End]

ID: SRS_026

When operating in Autonomous Platooning Mode, the FV shall have a means to request via the HMI to leave the platoon.

Parents: SRS_001
Classification: Requirement
[Requirement End]

2.2.5. Mode Transition Conditions

ID: SRS_027

The system shall transition from Manual Mode to Transitional Mode-Join when the following conditions are all met:

1. The transmission is in a forward gear.
2. A request has been received from the FV to join the platoon.
3. An acknowledgement has been received from the LV driver that the request from the FV has been accepted.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_028

All operator requests from either the FV or the LV (e.g., request by the FV to join the platoon, acknowledgement by the LV of the request to join the platoon) shall be communicated via the HMI.

Parents: SRS_027
Classification: Requirement
[Requirement End]

ID: SRS_029

The system shall transition from Transitional Mode-Join to Autonomous Platooning Mode once a safe, reasonable and stable speed and separation between the FV and LV has been achieved within acceptable tolerances.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_030

To transition from Transitional Mode-Join to Autonomous Platooning Mode, the separation between FV and LV shall be 50 m to 80 m.

Parents: SRS_029
Classification: Requirement
[Requirement End]

ID: SRS_031

To transition from Transitional Mode-Join to Autonomous Platooning Mode, the LV speed shall be between 5 mph and 55 mph.

Parents: root
Classification: Limitation
[Requirement End]

For the concept demonstration, platooning is not expected outside this speed range. Nothing in the system will prohibit initiation of platooning outside this range if the operators believe it is safe to do so, however.

ID: SRS_032

To transition from Transitional Mode-Join to Autonomous Platooning Mode, the relative velocity between FV and LV shall be between ± 4 mph.

Parents: SRS_029
Classification: Requirement
[Requirement End]

For this demonstration, the operating conditions of the platoon will be well-controlled. Vehicle loading conditions will be known and environmental conditions will be limited to dry roads without ice, calm winds, good visibility, etc. For these conditions, the Transition Mode-Join safe and reasonable distance has been estimated to be around 50 m. As operating conditions are expanded, this distance may be increased and the determination of safe distance would need to consider loading characteristics, braking capabilities, environmental conditions, and emergency braking response times (brake system pressure build rates), among other factors.

ID: SRS_033

The system shall transition from Autonomous Platooning Mode to Transitional Mode-Leave if a request to leave the platoon is received from the operator of the FV or a request to dissolve the platoon is received from the operator of the LV.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_034

The system shall transition from Transitional Mode-Leave to Manual Mode if the gap has reached the target (30 m) and an acknowledgment to transition to Manual Mode has been received by the FV driver.

Parents: root
Classification: Requirement
[Requirement End]

2.2.6. Other Mode-Related Requirements

ID: SRS_035

Whenever the platooning system is nominally controlling the FV's steering, braking and accelerator, the system shall allow the FV's driver to override the platooning system's input to these actuators by physically turning the steering wheel and / or depressing the brake or accelerator pedals.

Parents: root
Classification: Requirement
[Requirement End]

Note that the platooning system will continue to exert forces or torques on the actuators and the drivers will need to provide additional input to overcome these actuators. The objective, however, is to allow the drivers of the vehicle to be able to provide the ultimate control of their vehicles for reasons of safety.

2.3. V2V Communication

ID: SRS_036

V2V communication should meet IEEE 802.11 P.

Parents: root
Classification: For Information
[Requirement End]

ID: SRS_037
V2V communication should be possible within the range of the DSRC equipment installed in the vehicle.

Parents: root
Classification: For Information
[Requirement End]

2.4. Platoon Performance and Limitations

ID: SRS_038
While in autonomous platooning mode, both the LV and FV shall not perform maneuvers that exceed a lateral acceleration of 0.1 G

Parents: root
Classification: Limitation
[Requirement End]

ID: SRS_039
While platooning in autonomous mode, both the LV and FV shall not perform maneuvers that exceed a longitudinal acceleration of 0.3 G.

Parents: root
Classification: Limitation
[Requirement End]

ID: SRS_040
While in autonomous platooning mode, the platoon shall be able to complete maneuvers up to a maximum platoon speed not exceeding 55 mph.

Parents: root
Classification: Limitation
[Requirement End]

ID: SRS_041
In the event that the LV performs a panic stop, the FV must be able to maintain a minimum safe distance of half the platooning distance throughout the entire braking event.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_042
Upon restart of either vehicle, the system takes at least 2 minutes to initialize the V2V communication to enable proper data transfer between FV and LV. Hence, it is expected to wait for at least 2 minutes after vehicle restart to initialize the platoon request.

Parents: root
Classification: For Information
[Requirement End]

ID: SRS_043
Upon vehicle restart, the system needs either vehicle to traverse at least 200 m of travel to properly initialize the GPS tracking system. Hence, both the FV and LV need to be driven at least 200 m before initializing the platoon request.

Parents: root
Classification: For Information

[Requirement End]

2.5. Emergency Stop

ID: SRS_044

The LV driver shall have a hard wired means to shut down autonomous platooning.

Parents: root
Classification: Requirement
[Requirement End]

ID: SRS_045

The FV driver shall have a hard wired means to shut down autonomous function hardware and take manual control of the vehicle.

Parents: root
Classification: Requirement
[Requirement End]

TEXAS A&M TRANSPORTATION INSTITUTE TRUCK PLATOONING

DEMONSTRATION PLAN

Project Number	**Q011851**
Document Number	**RD 15/001733.1**
Date	**28 August 2015**
Client Confidential	

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REVISION HISTORY

Revision	Date	Sections Affected	Revisions	Changed by
1.0	28-Aug-2015	All	Initial Release	
2.0	30-Nov-2015		Response to Mo's Comments	CKI
3.0	20-Jan-2016		Response to Mo's Comments	MDM
4.0	06-June-2016	Section 3,4,5,6	General clarifications and updates	LEB

TABLE OF CONTENTS

TEXAS A&M TRANSPORTATION INSTITUTE (TTI) TRUCK PLATOONING DEMONSTRATION PLAN

1. INTRODUCTION

Texas Transportation Institute was selected by Texas Department of Transportation (TxDoT) to lead a transportation project with the objective of validating the feasibility and benefits of truck platooning.

Ricardo has been selected by TTI to lead the design, development and integration of a platooning control system on the truck platooning project. The project will use two Class 8 tractors with trailers. One vehicle will lead the platoon (LV) being professionally driven. The second vehicle, defined and the follow vehicle (FV), will follow the first vehicle using autonomous driving technology.

The purpose of this specification is to define the project's truck platoon demonstration requirements.

2. REFERENCES

In the event of a conflict between this document and the reference documents, this document shall take precedence.

ID	Document Title	Date/Revision
RD 15/001716.1	TTI Truck Platooning Operational Requirements	1.0
FHWA-JPO-12-021	Vehicle Information Exchange Needs for Mobility Applications Version 2.	2012

3. DEFINITION OF TERMS / ABBREVIATIONS

3.1. Definition of Terms

Below are definitions of key terms used in this document and for truck platooning technology.

"*forming a platoon***"** this refers to the bring together of the vehicles to create the platoon.

"*registering a platoon*" this refers to the platoon being registered to an administration authority that controls multiple platoons in its defined area.

"*dissolve*" this refers to the unregistering of the platoon with the controlling authority

"*disband*" this refers to the vehicles that were a platoon no longer operating or coordinating with each other.

"*maintaining a platoon*" this refers to the FV sustaining the same path and speed as the LV autonomously with a given tolerance.

"*join*" this refers to the FV linking up with the LV.

"*leave*" this refers to the FV unlinking with the LV.

"following gap" this refers to the distance between the rear of the LV and front of the FV.

3.2. Abbreviations

Term	Description
FV	Following Vehicle
LV	Lead Vehicle
PG	Proving Ground
SOW	Statement of Work

4. PLATOONING FUNCTIONS FOR THE PLATOONING DEMONSTRATION

Ricardo proposes to develop and deliver a two vehicle platoon with the following platooning functionality.

1. Joining a Platoon
2. Maintaining a Platoon
3. Leaving a Platoon
4. Disbanding the Platoon

The following features are not part of this projects SOW and may not be developed and will not be demonstrated in these phase of the project.

1. Registering a Platoon
2. Dissolving a Platoon
3. Any outside administration of the Platoon
4. Add additional vehicles to a formed Platoon
5. Emergency Manoeuvers / Crash avoidance (*see note 1.)*
6. Reverse Driving

Note 1. Ricardo will not be demonstrating this but will develop the capability within the platooning system. We will have algorithms that will use systems like wingman to warn the drivers of any possible issues.

5. PLATOON DEVELOPMENT AND DEMONSTRATION

In this section development and demonstration facilities, demonstrated platooning features and environmental and track conditions are discussed.

5.1. Platooning Development Facility (in Detroit)

The platooning system will be tested and developed near Detroit, Michigan. One of the facilities that may be used is Michigan Technical Resource Park. This facility includes a three lane, 1.75-mile concrete track with a ½ mile straightaway. A visual of the facility is in Figure 1.

Figure 1 - Plan of Michigan Technical Resource Park oval track.

5.2. Platooning Demonstration Facility (in Texas)

The demonstration of the platooning system is tentatively planned for the Texas A&M University Riverside Campus Texas shown in Figure 2 below. Use of this facility will be confirmed once all the truck performance specification has been finalized.

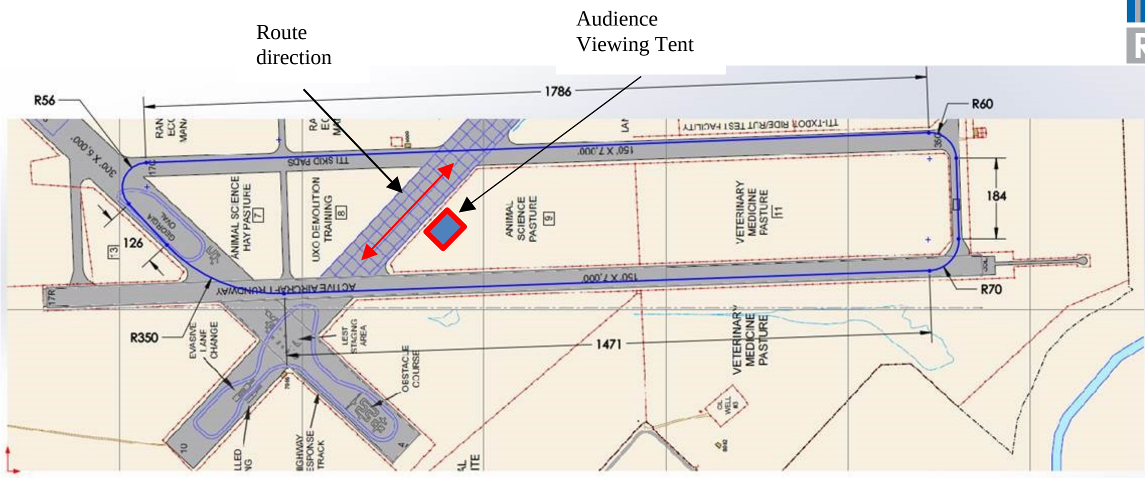


Figure 2 - Useable area at Riverside test facility

6. USE CASE DEMONSTRATION

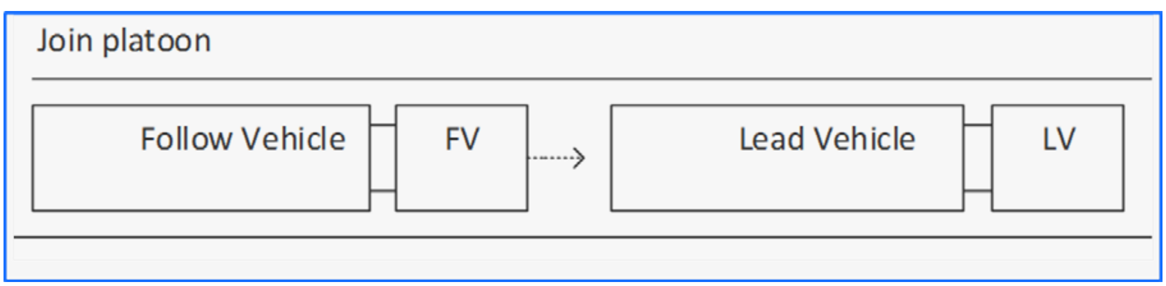
The TTI proof of concept platooning system demonstration will cover four (4) use cases. The use cases are: Join Platoon, Leave Platoon, Lane change while platooning and Gap maintenance including after Accelerate / Decelerate events while in the platoon. The use cases will be demonstrated, one at a time, during truck travel on the long leg of the demonstration track. Total demonstration time will be 20 minutes to complete the demonstration of all 4 use cases. Below are the descriptions the use cases and the activities involved to implement each required use case.

6.1. Demonstration Plan

The demonstration will start with a static review of the Trucks and the installed technology.

Upon completion of the static review the dynamic demonstration will begin with the following use case demonstrations:

6.2. Forming the Platoon



Forming of the platoon is a maneuver that involves a LV traveling on a roadway then receiving signal from another vehicle requesting to platoon. The FV will signal the LV via the HMI interface by pressing the “join platoon” button. The LV will receive the “join platoon” request via the LV HMI. The LV driver will accept the request by touching the “join platoon” button on the LV HMI. Once the platoon request is accepted by the LV the FV will automatically engage (notifying the drivers of each vehicle of the accepted platooning request). The FV will adjust its speed and follow distance and then establish the platoon. A message from the LV will be sent to the FV confirming platooning is engaged.

The forming of the truck platoon consists of the following features:

1. LV will maintain a speed of <= 40Mph. Speed based on track size, and time required to demonstrate use case – see Appendix.
2. FV will approach LV manually, adjusting its position to 15m to 50m and its relative velocity to within 2.5mps. The FV will then send a join the platoon request.
3. The FV will ask to join the LV using the HMI request to “join platoon” button. The LV will accept the request using its HMI system by pressing the accept “join platoon” button.
4. The FV will follow at a variable distance (10-50m) for this demonstration from LV, the HMI will signal to the FV that the request for platooning has been accepted. This indicates that it is safe for the FV to transition from manual driving to autonomous following.

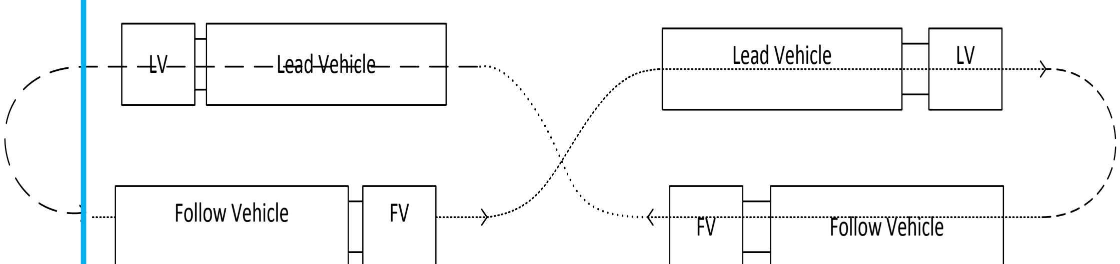
   Design Note: The FV driver will have 10 seconds to bring the FV in the delta Velocity and delta Distance range. On detecting the conditions within the 10 seconds time window, the FV will transition from manual to autonomous control.

5. The FV will begin platoon and send a confirmation message on the LV HMI.

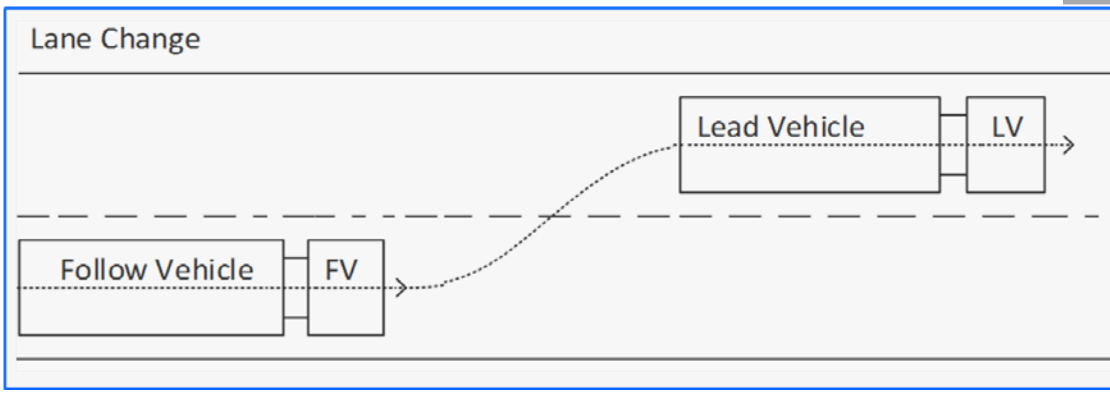
6.3. Following the Lead

Once the platoon is formed upon leaving the static demonstration, the next maneuver is the Figure “8” where the Platoon following capability is demonstrated. The first pass of the vehicles in front of the viewing tent will have the LV driver illustrate a hands free pass while the vehicles complete the first leg of the Figure “8”.

6.4. Follow the Lead



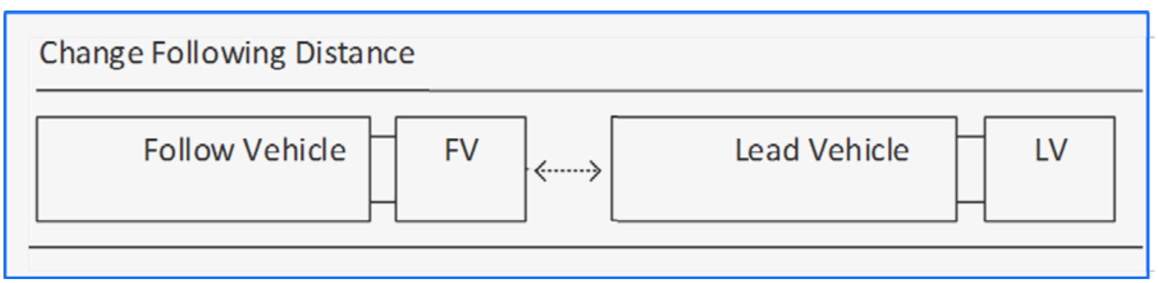
The detail of the activities required to complete the Figure “8” is described in the lane change maneuver.



While in platoon mode the LV and FV vehicles will demonstrate a lane change maneuver. The LV will change lanes and the FV will change lanes following the path created by the LV. The lane change use case is described by the following set of steps:

1. The LV will indicate a lane change by signaling the change using the vehicle lane change indicator.
2. The LV vehicle will make the lane change safely moving from the current lane to the adjacent lane.
3. The FV being in platoon mode will automatically make a lane change following and maintaining the path defined by the LV.
4. The defined speed of this use case demonstration is <=40 mph.

6.5. Maintaining the Platoon / Path Following



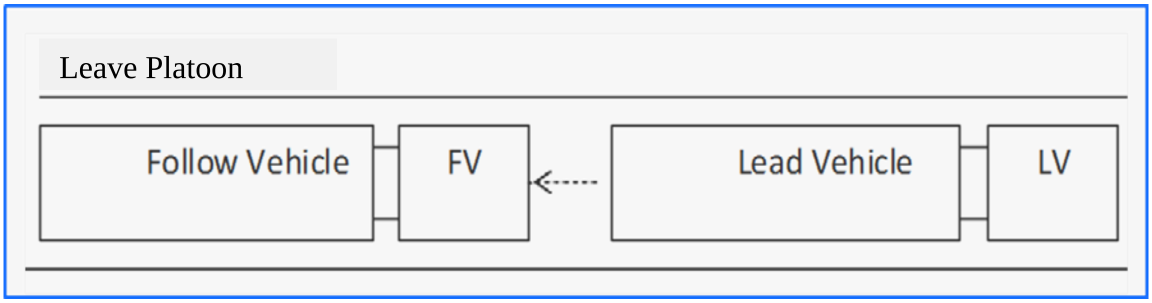
While in platooning mode the LV and FV will demonstrate the ability to change the following gap and maintain the following gap after an acceleration and deceleration event. This activity will be completed using the following steps.

1. The follow vehicle will select the desired distance using the HMI gap slider and selecting the desired gap size manually.
2. The FV will adjust its velocity to meet the selected gap size selection.

3. The LV will decelerate and accelerate manually while in platoon mode and the FV will change velocity to match the LV new adjusted speed at the selected gap size.

4. The vehicle will use a speed range of 30-40 mph for this use case demonstration.

6.6. Leaving / Disbanding the Platoon



While in platoon mode the LV and FV will demonstrate "leaving platoon" use case. This use case involves the follow steps:

1. The FV will request to leave the platoon via its HMI. This involves pressing the "leave platoon" button on the HMI.

2. Once the leave request is made the FV will go into a transition mode, slowing the vehicle to a gap distance of 30m for this demonstration. Once the gap size is reached 30m the FV vehicle will notify the driver and switch into manual mode.

6.7. Demonstration Environmental Conditions Requirements

The environmental conditions for the platooning demonstration should meet the following requirements:

1. Visibility to be above 250m distance.

2. Wind speed to be below 15 mph speed.

3. Road surface to be dry and free of standing water, snow, foreign objects, and sand/dust.

6.8. Demonstration Track Requirements

The demonstration facility must meet the following minimum requirements for the platooning demonstration:

1. Closed Area, only the demonstration vehicles to be on the track, spectators/pedestrian access restricted.

2. Reasonable unobstructed run-off area in the event of emergency maneuvers.

3. The system and vehicle are not intended for use on any public highways

4. Platooning will not be maintained on curves or banded surfaces.

7. APPENDIX

- Figure #3: Steady state time versus vehicle speed.
- Figure #4: Acceleration / Deceleration curve over vehicle speed versus distance and vehicle speed versus time.

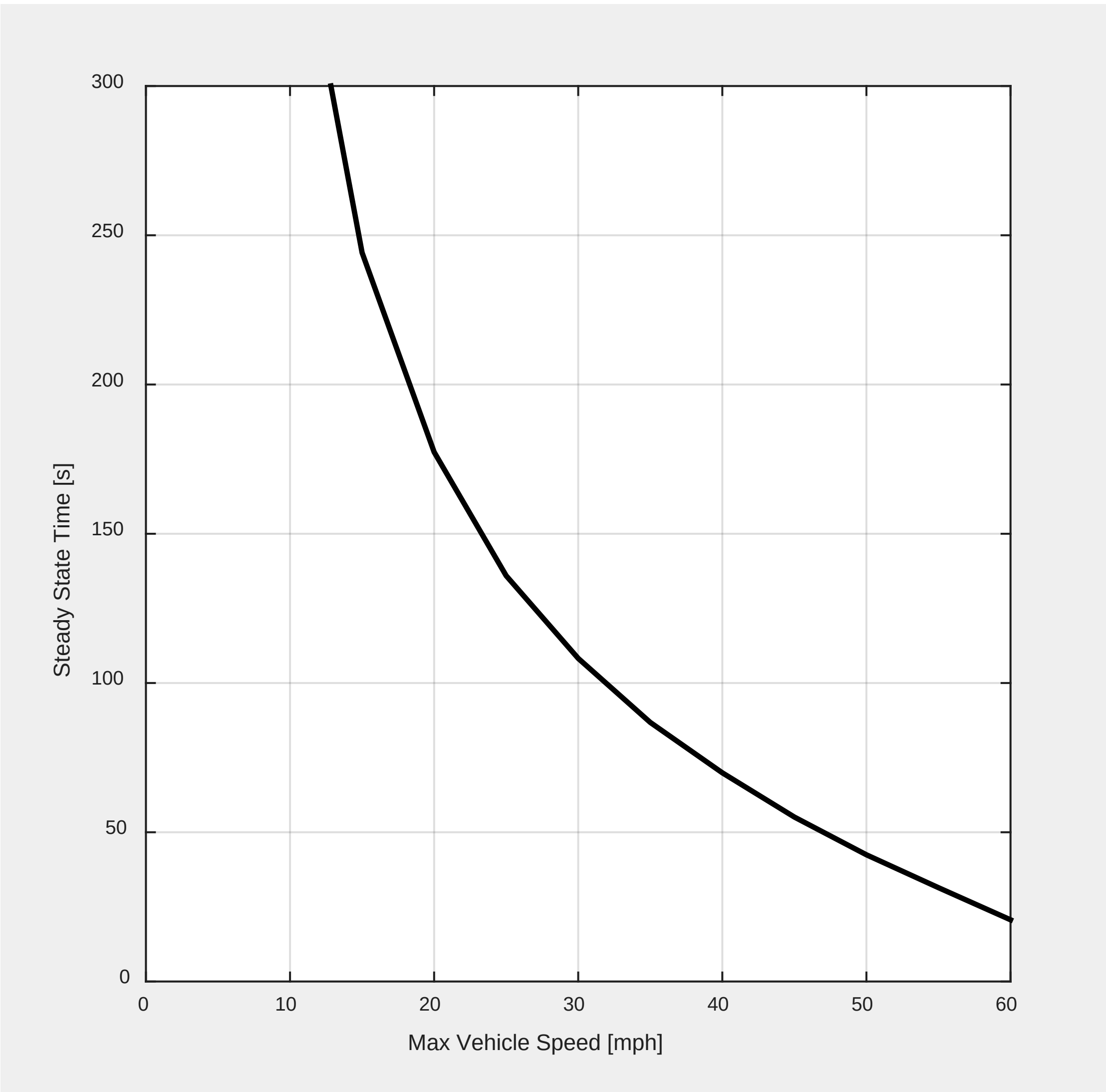


Illustration of speed verse steady state time on the longest straight away at the demonstration track. At 30 mph the trucks have ~ 108 seconds of steady state test time on the straight away. At 4 0mph the trucks have ~70 seconds of steady state testing time on the test track. See the figure below.

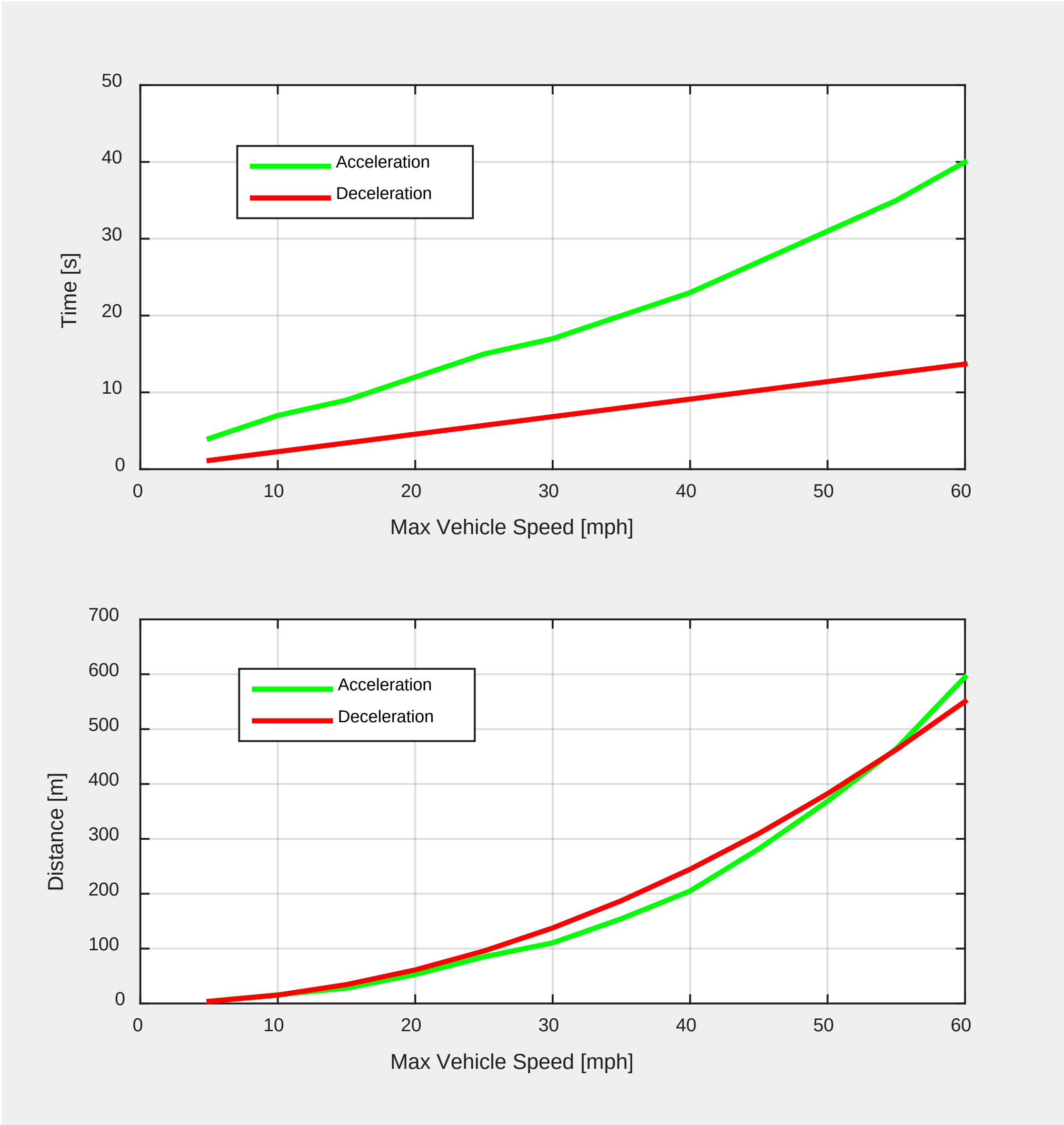


Figure #3: Vehicle speed versus steady state time at demonstration facility in College Station