# Truck Platooning Early Deployment Assessment – Independent Evaluation

## Expanded Analysis Plan

www.its.dot.gov/index.htm
**Final Report — August 2022**
**Publication Number: FHWA-JPO-22-962**

U.S. Department of Transportation

Produced by Noblis Inc.
U.S. Department of Transportation
Intelligent Transportation Systems (ITS) Joint Program Office

## Notice

# Technical Report Documentation Page

**1. Report No.**
**FHWA-JPO-22-962**

**2. Government Accession No.**

**3. Recipient's Catalog No.**

**4. Title and Subtitle**

Truck Platooning Early Deployment Assessment – Independent Evaluation: Expanded Analysis Plan

**5. Report Date**
August 17, 2022.

**6. Performing Organization Code**

**7. Author(s)**

Sampson Asare, James Chang, and Barbara Staples

**8. Performing Organization Report No.**

**9. Performing Organization Name and Address**

Noblis, Inc.,
500 L'Enfant Plaza, S.W., Suite 900
Washington, D.C. 20024

**10. Work Unit No. (TRAIS)**

**11. Contract or Grant No.**

DTFH61-16-D-00036

**12. Sponsoring Agency Name and Address**

ITS-Joint Program Office
1200 New Jersey Avenue, S.E.
Washington, DC 20590

**13. Type of Report and Period Covered**

**14. Sponsoring Agency Code**

**15. Supplementary Notes**

Work performed for: Gene McHale and Hyungjun Park (FHWA, TOCOR)

**16. Abstract**

The United States Department of Transportation (USDOT) recognizes that cooperative automated driving systems will have a transformative impact on how the nation's highways will operate in the future. One of the proposed near-term services is truck platooning. Truck platooning promises fuel savings to platooning trucks by enabling them to follow each other more closely, while still in a safe manner. In the future, the commercial trucking industry is planning to deploy communications-based truck platooning systems. System-wide impacts and the impact on truck drivers, fleet owners, and light duty vehicle drivers still need to be assessed for operational and safety impacts. To this end, the USDOT selected three teams (Battelle, California PATH, and CDM Smith) to participate in the "Truck Platooning Early Deployment Assessment, Phase 1" project. The objective of Phase 1 was to develop a concept and proposal for deploying and assessing a commercial truck platoon system. In Phase 2, California PATH has been selected to conduct the actual field operational testing and assessment of truck platoons. This is subject to a successful Operational Readiness Test and subsequent USDOT decision to proceed with the field operational test (FOT).

As the Phase 2 Independent Evaluator (IE), Noblis has been tasked to develop a plan for expanded analysis that is needed to provide generalized answers to truck platooning research questions. The purpose of this report is to present the expanded analysis plan. The expanded analysis will cover truck platoon impacts areas that are of interest to FHWA but not covered in PATH's Test and Evaluation Plan for the Phase 2 Field Operational Test. These include:

- Analyzing more truck platoons;
- Expanded geographical analysis; and
- Supplementary analysis such as impacts of truck platoons on traffic flow, surrounding vehicle behavior, etc.

This Expanded Analysis Report was written to support the FOT which may take place in the future.

**17. Key Words**

Truck platooning, performance measures, requirements, prioritization

**18. Distribution Statement**

**19. Security Classif. (of this report)**
Unclassified

**20. Security Classif. (of this page)**
Unclassified

**21. No. of Pages**
46

**22. Price**

**Form DOT F 1700.7 (8-72)** **Reproduction of completed page authorized**

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# Executive Summary

***Please note that, at the time this report was developed, the PATH Phase 2 project had experienced delays in progressing toward the FOT stage. This Expanded Analysis Report was written to support the FOT, which may take place in the future.***

## Background

The United States Department of Transportation (USDOT) recognizes that cooperative automated driving systems will have a transformative impact on how the nation's highways will operate in the future. One of the proposed near-term applications is truck platooning. Truck platooning has the potential to increase fuel savings to platooning trucks by enabling them to follow each other more closely, while still in a safe manner. The Federal Highway Administration (FHWA), as part of the Exploratory Advanced Research (EAR) program, funded exploratory research to assess and study two and three truck platooning technologies and operations (1). In the future, the commercial trucking industry may pursue the deployment of truck platooning systems based on vehicle-to-vehicle (V2V) communications. System-wide impacts, infrastructure impacts, and the impact on truck drivers, fleet owners, and light duty vehicle drivers still need to be assessed for operational and safety impacts.

In order to understand the potential impacts of truck platooning systems, FHWA issued a Broad Agency Announcement (BAA) for "Truck Platooning Early Deployment Assessment" on August 30, 2018, to conduct a multi-state, long-haul field test of truck platooning operations with similar trucks (e.g., same fleet, size, and make/model) with minimum SAE Level 1 automation capabilities. Specific research questions to be answered included:

- What are the human-factors impacts on truck drivers in long-haul operation of a truck platoon?
- How is other road users' behavior impacted by the presence of truck platoon operations?
- How does the gap between the trucks impact the costs / benefits of platooning (e.g., fuel savings, safety, operating costs, vehicle maintenance, mobility/travel time) as well as the risks (e.g., number of cut-ins, truck driver's behavior/acceptance/fatigue)?
- What are the benefits of truck platooning to fleet owners?
- What are the policy, operational, and safety impacts of truck platooning?

The "Truck Platooning Early Deployment Assessment" project is divided into two phases. The objective of Phase 1 is to develop a concept and proposal that sets the stage for an assessment of a commercial motor vehicle platooning field operational test that has an observable and measurable near-term impact. Three teams were selected by FHWA to participate in the 9-month Phase 1 project (hereafter referred to as Phase 1 Awardees). The Phase 1 Awardee teams were led by Battelle, California Partners for Advanced Transportation Technology (PATH), and CDM Smith (2). Only the Phase 1 Awardees were eligible to submit Phase 2 proposals. Phase 1 was completed in December 2019 and FHWA issued a single award for Phase 2 of the BAA in July 2020.

Under Phase 2 the selected Phase 2 Awardee, led by California PATH, would implement and conduct the actual field operational testing (FOT) and assessment of truck platoons. Specific tasks to be conducted by PATH in Phase 2 include, but are not limited to, develop a comprehensive deployment plan, update and establish partnerships, refine and install the system, conduct system acceptance testing, obtain human use approval, recruit and train truck drivers, and complete operational readiness testing. Subject to a USDOT decision to proceed, PATH will conduct field operational testing, collect and report data and performance measures, and finally evaluate the collected data.

Noblis was awarded a task order to support Intelligent Transportation Systems Joint Program Office (ITS JPO) and its partner agencies (primarily FHWA and FMCSA) as the Independent Evaluator (IE) for Phase 2. Among the responsibilities of the Phase 2 Independent Evaluator (IE) is the need to develop a plan for expanded analyses that are needed to provide generalized answers to truck platooning research questions. The expanded analysis will cover truck platoon impacts areas that are of interest to FHWA but not covered in PATH's Test and Evaluation Plan for the Phase 2 FOT.

# Phase 2 Truck Platoon Field Operational Test (FOT)

The planned 30-month Phase 2 truck platoon project is being led by PATH and its team consisting of Roly's Trucking (fleet operator partner), Westat (human factors expert), Cambridge Systematics (stakeholder engagement), and with key technical support from Volvo Group (OEM partner). During the initial 15 months (approximate), PATH will execute tasks in the implementation stage to prepare for the FOT. Upon a successful Operational Readiness Test and subsequent USDOT decision to proceed with the FOT, PATH will conduct a one-year truck platoon FOT on a 1,400-mile route that includes a segment of the I-10 corridor between Roly's main terminal in Rancho Cucamonga, California and west Texas, and then a stretch of I-20 to a Roly's terminal in Fort Worth, Texas.

The truck platoon FOT will consist of four new Volvo model VNL-64T760 truck tractors with 500 horsepower engines and a 12-gear electronic transmission, engine brake and service brake. These trucks will be integrated into the normal interstate freight operations of Roly's trucking along the FOT route. One of the four trucks to be used in the FOT will be used as a “control” or “reference” truck that will be driven individually along the same route at about the same time as the truck platoon to provide a baseline for comparison with the platooned trucks.

The number of platoon trips to be driven during the test period will depend on the shipping demand from Roly's customers and how Roly's decides to serve that demand. Under the most optimistic conditions, each truck could be driven in platoon for two round trips per week, or about 100 round trips (200 one-way trips) over the year-long test. Under the most pessimistic conditions, each truck would be driven one round trip per week, which would provide for about 50 one-way platoon trips over the year-long test. Factoring in the roughly 1,400-mile (one-way) trip distance and four trucks, this equates to between 280,000 miles and 1,120,000 miles of data collection for all four trucks in the truck platoon FOT.

# Scope of Expanded Analysis

The technical scope of the Expanded Analysis Plan focuses on (i) analyzing the impacts of truck platooning in areas of interest to FHWA but not covered in PATH's FOT assessment (as captured in their Test and Evaluation Plan) and (ii) analytical techniques/methodologies that would provide answers to key FHWA research questions but not within the scope of PATH's FOT assessment. These include:

- **Analyze More Truck Platoons:** This involves approaches for testing the sensitivity of truck platooning impacts to truck platoon market penetration rates. Subject to USDOT's decision to proceed with the FOT, assessment of the Phase 2 FOT will be limited to the three trucks that would drive in a “platoon” mode. Consequently, their analysis will not be able to provide insights on how truck platoon impacts change as the penetration rate of platooning trucks changes. The sensitivity analysis helps to put an envelope around the impacts of truck platooning.

- **Expanded Geographic Analysis:** In addition to analyzing the impacts of truck platooning that would be experienced on the planned 1,400-mile FOT route, the expanded analyses will extrapolate the impacts of truck platooning to the regional and national levels in order to generalize these impacts.
- **Supplementary Analysis:** This will focus on additional truck platoon impact analysis. These include impacts on surrounding vehicle behavior, traffic flow, and pavements/bridges.

# Conclusions

This report is an outcome of the Phase 2 IE's support to ITS JPO and its partner agencies (primarily FHWA and FMCSA) on the "Truck Platooning Early Deployment Assessment, Phase 2" project. The report presents a plan to perform additional analysis on truck platoon impact areas that would not be covered by PATH's FOT analysis. The report includes:

- Approach for analyzing the impacts of truck platoon as market penetration changes;
- Analysis Approach for extending the benefits of the truck platoon FOT beyond the geographical boundaries of the FOT route. This involves extrapolating the benefits of truck platoon (as deployed in the FOT) to regional and national levels; and
- Approach to assess the impacts of truck platoon on surrounding vehicle behavior.

The following aspects of truck platoon impacts are recommended for future research:

- The impacts of truck platoons on the structural integrity and maintenance lifecycle of pavement and bridges considering different platoon sizes and gap settings;
- Since the FOT route is within states that are less likely to experience wintery conditions such as icy roads and snow, the performance and safety of truck platoons in wintery conditions should be studied; and
- The FOT involves use of only Volvo trucks with PATH's CACC platooning implementation. In the future, the potential for platooning using trucks from different manufacturing brands should be studied.

# 1 Introduction

***Please note that, at the time this report was developed, the PATH Phase 2 project had experienced delays in progressing toward the FOT stage. This Expanded Analysis Report was written to support the FOT, which may take place in the future.***

The United States Department of Transportation (USDOT) recognizes that cooperative automated driving systems will have a transformative impact on how the nation's highways will operate in the future. One of the proposed near-term applications is truck platooning. Truck platooning has the potential to increase fuel savings to platooning trucks by enabling them to follow each other more closely, while still in a safe manner. The Federal Highway Administration (FHWA), as part of the Exploratory Advanced Research (EAR) program, funded exploratory research to assess and study two and three truck platooning technologies and operations (1). In the future, the commercial trucking industry may pursue the deployment of truck platooning systems based on vehicle-to-vehicle (V2V) communications. System-wide impacts, infrastructure impacts, and the impact on truck drivers, fleet owners, and light duty vehicle drivers still need to be assessed for operational and safety impacts.

In order to understand the potential impacts of truck platooning systems, FHWA issued a Broad Agency Announcement (BAA) for "Truck Platooning Early Deployment Assessment" on August 30, 2018 to conduct a multi-state, long-haul field test of truck platooning operations with similar trucks (e.g., same fleet, size, and make/model) with minimum SAE Level 1 automation capabilities. Specific research questions to be answered included:

- What are the human factors impacts on truck drivers in long-haul operation of a truck platoon?
- How is other road users' behavior impacted by the presence of truck platoon operations?
- How does the gap between the trucks impact the costs / benefits of platooning (e.g., fuel savings, safety, operating costs, vehicle maintenance, mobility/travel time) as well as the risks (e.g., number of cut-ins, truck driver's behavior/acceptance/fatigue)?
- What are the benefits of truck platooning to fleet owners?
- What are the policy, operational and safety impacts of truck platooning?

The "Truck Platooning Early Deployment Assessment" project is divided into two phases. The objective of Phase 1 is to develop a concept and proposal that sets the stage for an assessment of a commercial motor vehicle platooning field operational test that has an observable and measurable near-term impact. Three teams were selected by FHWA to participate in the 9-month Phase 1 project (hereafter referred to as Phase 1 Awardees). The Phase 1 Awardee teams were led by Battelle, California Partners for Advanced Transportation Technology (PATH), and CDM Smith (2). Only the Phase 1 Awardees were eligible to submit Phase 2 proposals. Phase 1 was completed in December 2019 and FHWA issued a single award for Phase 2 of the BAA in July 2020.

Under Phase 2, the selected Phase 2 Awardee, led by California PATH, would implement and conduct the actual field operational testing and assessment of truck platoons. Specific tasks to be conducted by PATH in Phase 2 include, but are not limited to, develop a comprehensive deployment plan, update and establish partnerships, refine and install the system, conduct system acceptance testing, obtain human use approval, recruit and train truck drivers, and complete operational readiness testing. Subject to a USDOT decision to proceed, PATH will conduct field operational testing, collect and report data and performance measures, and finally evaluate the collected data.

Noblis was awarded a task order to support ITS JPO and its partner agencies (primarily FHWA and FMCSA) as the Independent Evaluator (IE) for Phase 2. The role of the IE in Phase 2 is to:

- Provide technical support service to the Phase 2 awardee during the implementation stage to refine a comprehensive deployment plan, establish partnerships, obtain human use approval, recruit and train truck drivers, and refine and install truck platooning systems.
- Participate in and provide technical support for the operational readiness testing to confirm that all the implementation tasks are complete and all the required conditions are ready to initiate an actual field operational test, in support of USDOT's Go/No-Go decision.
- Conduct periodic quality checking of the data (raw and processed) and performance measures reported by the Phase 2 awardee during the field operational test to ensure that the collected data and calculated performance measures meet the requirements as described in the test and evaluation plan.
- Develop a plan for expanded analyses that could be performed to provide generalized answers to the research questions related to truck platooning. **This document is the Expanded Analysis Plan**.

## 1.1 Phase 2 Truck Platoon Field Operational Test (FOT)

The planned 30-month Phase 2 truck platoon project is being led by PATH and its team consisting of Roly's Trucking (fleet operator partner), Westat (human factors expert), Cambridge Systematics (stakeholder engagement), and with key technical support from Volvo Group (OEM partner). During the initial 15 months (approximate), PATH will execute tasks in the implementation stage to prepare for the FOT. Upon a successful Operational Readiness Test and subsequent USDOT decision to proceed with the FOT, PATH will conduct a one-year truck platoon FOT on a 1,400-mile route that includes a segment of the I-10 corridor between Roly's main terminal in Rancho Cucamonga, California and west Texas, and then a stretch of I-20 to a Roly's terminal in Fort Worth, Texas as shown in Figure 1 below.

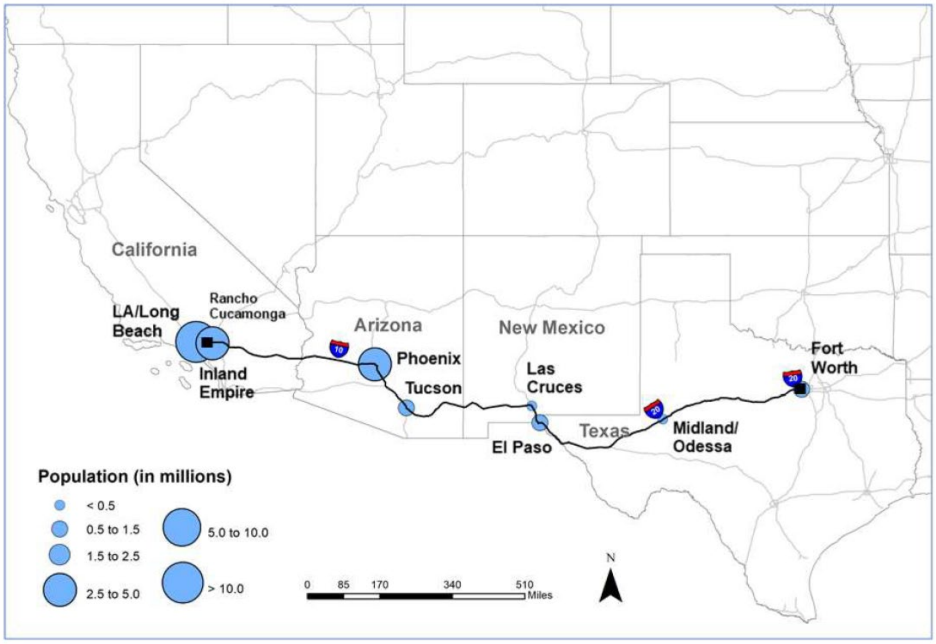


**Figure 1. Map of Truck Platooning FOT Route (Source: PATH)**

Subject to USDOT's decision to proceed with the FOT, PATH's Phase 2 FOT will consist of four new Volvo model VNL-64T760 truck tractors with 500 horsepower engines and a 12-gear electronic transmission, engine brake and service brake. These trucks will be integrated into the normal interstate freight operations of Roly's trucking along the FOT route. One of the four trucks to be used in the FOT will be used as a "control" or "reference" truck that will be driven individually along the same route at about the same time as the truck platoon to provide a baseline for comparison with the platooned trucks. This implies that it will experience the same traffic and weather conditions that provides an opportunity for a direct comparison between the platooned trucks and non-platooned control truck in many areas including:

- Fuel consumption
- Truck driver behavior, including attentiveness and fatigue
- Interactions with surrounding traffic and their safety implications
- Travel time between same origin and destination (taking into account time to get the platoon assembled at the origin).

The number of platoon trips to be driven during the test period will depend on the shipping demand from Roly's customers and how Roly's decides to serve that demand. Under the most optimistic conditions, each truck could be driven in platoon for two round trips per week, or about 100 round trips (200 one-way trips) over the year-long test. Under the most pessimistic conditions, each truck would be driven one round trip per week, which would provide for about 50 one-way platoon trips over the year-long test. Factoring in the roughly 1,400-mile (one-way) trip distance and four trucks, this equates to between 280,000 miles and 1,120,000 miles of data collection for all four trucks in the truck platoon FOT. Note that not all these miles will be driven in "platoon" mode; however, they will all be used in evaluating the impacts of truck platooning. Since the truck platoon FOT is a year long, the large quantity of data to be collected will represent a full range of weather conditions encountered on the test route. In addition, the truck platoon FOT is expected to include both daytime and night-time driving to help understand whether platoon operations vary based on lighting conditions.

The three FOT trucks that will be driving in “platoon mode” will be equipped with a Cooperative Adaptive Cruise Control (CACC) technology that builds directly on the system that PATH and Volvo Group developed under their FHWA EAR project (1). In addition to the CACC system, they will be equipped with a supplementary Driver-Vehicle Interface (DVI) to enable platoon drivers to readily understand the state of all three trucks that are driving together and to safely operate in public traffic. Finally, the FOT trucks will be instrumented with video and sensor capabilities to observe driver behavior (for all four trucks) and video and LIDAR sensors to measure the behavior of surrounding vehicles that drive within proximity of the three trucks that will drive in “platoon” mode (2).

## 1.2 Purpose of the Report

The Phase 2 FOT, which is subject to USDOT’s decision to proceed with the FOT, will be limited in scope with specific focus on the FOT route and four test trucks. This limits the ability of PATH’s evaluation to answer all five USDOT research questions outlined in the Phase 1 BAA. As a result, USDOT requires expanded analyses to complement PATH’s FOT evaluation. The purpose of this document is to present an expanded analysis plan that leverages FOT data and PATH’s limited evaluation results to conduct a comprehensive assessment of truck platooning impacts from a more general point of view.

## 1.3 Organization of the Report

This report is organized as follows:

- *Chapter 2 Scope of Expanded Analysis Plan:* Discusses the scope of the Expanded Analysis Plan at a high level;
- *Chapter 3 Analyze More Truck Platoons:* Presents the analysis approach for testing the sensitivity of truck platooning impacts to truck platoon market penetration rates;
- *Chapter 4 Expanded Geographical Analysis:* Discusses in detail the process for leveraging PATH’s FOT data and evaluation results to conduct analyses beyond the physical boundary of the FOT route, and generalizing the impacts of truck platooning at the regional and national levels;
- *Chapter 5 Supplementary Analyses:* Discusses approaches for analyzing truck platooning impact areas that were identified as important in the Phase 1 Performance Measure Requirements (21) but not covered by PATH’s evaluation; and
- *Chapter 6 Conclusion:* Summarizes the key tenets of the Expanded Analysis Plan.

# 2 Scope of Expanded Analysis Plan

The scope of the Expanded Analysis Plan is constrained in two ways—technical and geographical. The technical scope defines the level and types of technical analyses that would be conducted as part of the expanded analysis. The geographical scope defines the spatial extent within which the technical analyses would be conducted. Both are briefly discussed below.

## 2.1 Technical Scope

The technical scope of the Expanded Analysis Plan focuses on (i) analyzing the impacts of truck platooning in areas of interest to FHWA but not covered in PATH's FOT assessment (as captured in their Test and Evaluation Plan; see Appendix) and (ii) analytical techniques/methodologies that would provide answers to key FHWA research questions but are not within the scope of PATH's FOT assessment. These include:

- **Sensitivity Analysis of Truck Platooning Impacts:** This involves approaches for testing the sensitivity of truck platooning impacts to truck platoon market penetration rates. PATH's FOT assessment, which is subject to USDOT's decision to proceed with the FOT, will be limited to the three trucks that would drive in "platoon" mode. Consequently, their analysis will not be able to provide insights on how truck platoon impacts changes as the penetration rate of platooning trucks changes. The sensitivity analysis helps to put an envelope around the impacts of truck platooning. This is discussed in detail in Chapter 3.
- **Impacts of Truck Platooning on Surrounding Vehicles' Behavior:** This focuses on the analysis approach for evaluating how truck platooning affects the tactical behavior (e.g., lane selection, speed selection, etc.) of surrounding vehicles. This is presented in Chapter 5.
- **Impacts of Truck Platooning on Traffic Flow:** This focuses on the analysis approach for estimating the operational impacts of truck platooning in a travel corridor. Specifically, this will provide insights on how truck platoon impacts mobility variables in a travel corridor such as average travel time, average speed, vehicle throughput, etc. Chapter 5 presents detailed discussions on this topic.
- **Impacts of Truck Platooning on Pavements & Bridges:** This will focus on analytical approaches for assessing impacts of truck platooning on the structural health and maintenance cycle of pavements and bridges. This is presented in Chapter 5.

## 2.2 Geographical Scope

Although the Phase 2 FOT (which is subject to USDOT's decision to proceed with the FOT) will be conducted on a 1,400-mile route between Roly's Trucking main terminals between Rancho Cucamonga, California and Forth Worth, Texas (see Figure 1), the expanded analyses will not be limited to the geographical boundaries of this test route. In addition to analyzing the impacts of truck platooning on surrounding vehicle behavior and traffic flow within the FOT route, the expanded analyses will extrapolate the impacts of truck platooning to the regional and national level in order to generalize these impacts. The Expanded Analysis Plan discusses the processes and analytical approaches for “scaling up” the impacts of truck platooning beyond the geographical limits of the FOT route.

Note that the scope of the Expanded Analysis Plan will not include field data collection. The expanded analyses will rely mainly on field data collected by PATH during the one-year FOT and shared with the FHWA.

Furthermore, the scope of the expanded analyses is limited to evaluating the impacts of truck platooning as deployed in the FOT. The expanded analyses will not include truck platooning technologies deployed through other projects other than FHWA’s “Truck Platooning Early Deployment Assessment” project. Detailed discussions on the expanded geographical analysis is presented in Chapter 4.

# 3 Analyzing More Truck Platoons

The truck platoon FOT, which is subject to USDOT's decision to proceed with an FOT, will consist of three platooning trucks and one "control" truck traveling along the test route. Consequently, the estimated impacts from the truck platoon FOT will be based on these limited number of trucks. In order to understand the full range of truck platoon impacts, there is a need to test different truck platoon penetration rates. This chapter discusses the analysis approach for testing the sensitivity of truck platooning impacts to truck platoon penetration changes.

The approach for analyzing more truck platoons involves using microsimulation models to simulate truck platoon behavior and testing different penetration rates under different operational conditions. This approach is further discussed in the subsequent sections below.

## 3.1 Microsimulation Modeling

Microscopic simulation modeling simulates the movement of individual vehicles based on car-following and lane-changing theories (3). It offers a cost-effective approach to addressing USDOT's research questions on traffic flow and overall system-wide impacts of truck platooning. Microsimulation modeling has been used in many USDOT (4) and other truck platooning projects (5). In this approach, truck platoon operations will be modeled and replicated in a simulation environment using data collected from the FOT. Analysis of the modeling and simulation output would provide answers to the research questions of interest. The IE will follow the procedures described in Sections 3.1.1 and 3.1.2 to develop microsimulation models based on which sensitivity analysis described in Section 3.2 will be conducted. Figure 2 provides an overview of the microsimulation modeling process.

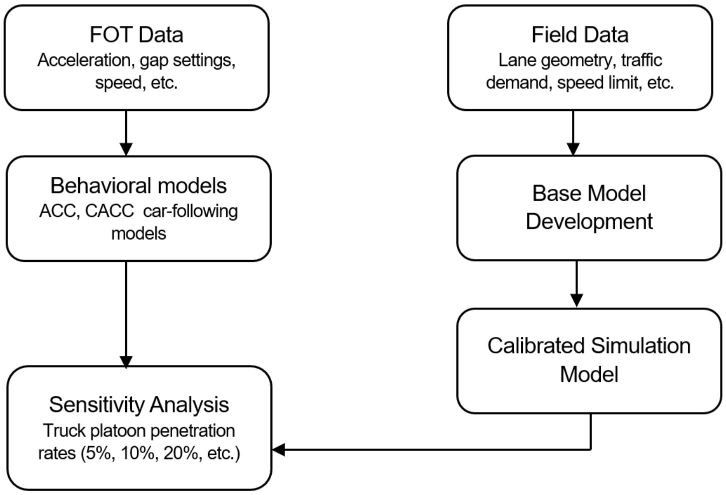


**Figure 2. Microsimulation Modeling Process (Source: Noblis)**

## Development of Behavioral Models

The FOT truck platoon concept will involve a lead truck followed by two other trucks. The platooning trucks would have only SAE level 1 automation capabilities; hence, only longitudinal vehicle control (i.e., car-following) is automated (6). The platoon truck drivers are expected to perform the remainder of the driving task (e.g., steering, observing roadway driving conditions, detection of roadway hazards, etc.). In order to develop a microsimulation model, the IE would first develop a behavioral model that replicates the car-following behavior between the lead truck and the following trucks. At any given instant, the platoon trucks will drive in manual, adaptive cruise control (ACC), or cooperative adaptive cruise control (CACC) mode.

- **Manual Mode**—A truck is driving in manual mode if the driver is in full control of the car-following activity. This implies that the driver decides the speed of the truck.
- **ACC Mode**—In ACC mode, a truck's car-following behavior is automated. The speed of a truck in ACC mode is regulated by the time-gap settings and the speed of the lead vehicle.
- **CACC Mode**—The CACC mode is an improved version of ACC mode. The improvement comes from vehicle-to-vehicle (V2V) communication capabilities that allows trucks driving in CACC mode to quickly and effectively adjust their speed and time-gap with respect to lead vehicles. This implies that trucks in CACC mode are able to travel more closely together than those in ACC mode.

During active platoon engagements, it is expected that the lead truck will drive in ACC mode, while the two following trucks will drive in CACC mode. However, truck platoon drivers are free to choose the mode of operation based on prevailing driving conditions.

The IE would develop car-following models for each of the driving modes described above using field data from the FOT. Although trucks driving in manual mode would not engage in platooning activities, a car-following model is still needed because of the potential of vehicle cut-ins. Vehicles cutting in and cutting out of the platoon may cause a following truck to operate in manual mode for a period of time before returning to active platooning. Hence, a car-following model for manual mode is needed. In addition, car-following models would be developed for different operational conditions of interest (e.g., rainy conditions, near on/off ramps, urban and suburban environments, etc.) if necessary. The data elements that would be needed for car-following model development are listed below.

- **Acceleration Data**—This data measures the rate of change in speed for lead and following trucks as they engage in both platooning and non-platooning driving. This will include both minimum and maximum accelerations experienced.
- **Deceleration/ Braking Data**—This data measures deceleration and braking maneuvers experienced by lead and following trucks as they engage in platooning and non-platooning driving. This will include both minimum and maximum decelerations recorded.
- **Time-gap Data**—This is the time-gap selected by drivers of the following trucks during active platoon engagements. The time-gap ranges from 1.1s – 1.9s for ACC mode and 0.6s–1.8s for CACC mode.
- **Speed Data**—This is the observed speeds of lead and following trucks as they engage in both platoon and non-platoon driving.
- **Operational/Environmental Data**—This includes congestion levels, weather condition, lighting condition (daytime vs. nighttime) and other prevailing factors during the time of travel. This data

would help the IE to determine the different operational conditions and determine if there is a need for different car-following models for different operational conditions.

In general, the car-following model can be expressed mathematically as shown below in equation 1

$$Acceleration\ = f\ (subject\ truck\ speed\ and\ timegap\ settings, lead\ truck\ speed) \quad \text{(Eq. 1)}$$

As shown in equation 1, the car-following model calculates the target acceleration for a subject truck by taking into account the subject vehicle's own speed and time-gap settings as well as the speed of the lead truck (i.e., the relative speed of following truck to lead truck). In a simulation model, this calculation is repeated at regular intervals (e.g., every second). The mathematical nature of the car-following model (e.g., linear, quadratic, exponential, etc.) would be determined by the IE during the model fitting process.

Although the FOT truck platoon concept is a three-truck platoon, the size of the platoon may not remain the same throughout the FOT. Due to potential cut-ins by other vehicles, a split may occur, leading to a two-truck platoon. Similarly, depending on the shipping demand from Roly's customers and how Roly's decides to serve that demand, there may be instances where only a two-truck platoon would be deployed instead of the regular three-truck platoon. Consequently, the IE would investigate to determine whether separate car-following models are needed for two-truck and three-truck platoons.

## Develop Base Model

The next step in the simulation modeling process is to develop a base model of the FOT route (i.e., transportation network). There are many microsimulation modeling software tools that can be used to build a base model. The IE would work with USDOT to determine the appropriate tool to use. Since the FOT route is about 1,400 miles long, it would be impossible to model the entire route due to size limitations in microscopic simulation software tools. Therefore, the IE would work with USDOT to determine specific segments along the FOT route which will be modeled. The selected segments would be those that are likely to provide answers to USDOT's research questions. Preliminary segments to consider include:

- Segments with high level of active truck platoon engagements
- Segments with on and off-ramps
- Segments with grades
- Segments in/around urban areas, suburban/metropolitan areas, and rural/intercity areas.

After identifying the FOT route segment(s) to model, the IE would specify and collect data needed to develop the base model. The key data elements for base model development include:

- Link geometry data (e.g., number of lanes, lane width, grade, etc.)
- Traffic control data (e.g., ramp metering)
- Traffic operations and management data (e.g., speed limits, lane use restrictions, etc.)
- Traffic demand data (e.g., number of vehicles, vehicle mix, etc.)
- Driver behavior data (e.g., driver attentiveness)

The IE would use the above data as well as other contextual data to develop the base model. In addition, the IE would specify simulation parameters such as length of simulation time, performance measures of interest, and remediate software and coding errors.

### Calibration of Simulation Model

Calibration is the adjustment of model parameters to improve the model's ability to reproduce time-dynamic system performance observed under specific travel conditions (7). For each modeled segment and operational condition of interest, the base model would be calibrated to the observed field conditions, including observed surrounding vehicle behaviors (e.g., lane choice selection, lane changing behavior, speed behavior, merging behavior, adjacent lane utilization). Calibration performance measures and acceptance criteria outlined in the Traffic Analysis Toolbox Volume III 2019 Update (7) would be used to ensure that the model is well calibrated.

## 3.2 Sensitivity Analysis

A sensitivity analysis is a targeted assessment that focuses on changing the values of a specific model input variable and observing the changes in model output. The IE would use the calibrated simulation model to evaluate how changes in truck platoon penetration rates affects the impacts of truck platoon. This would help to determine range of benefits associated with truck platoons. To conduct the sensitivity analysis, different penetration rates of truck platoon would be tested in the simulation model while all other variables are held constant. The IE would work with USDOT to determine the appropriate penetration rates to be tested in sensitivity analysis. Examples of truck platoon penetration rates that could be tested include 5%, 10%, 15%, 20%, 25%, etc. Some factors to be considered in the sensitivity analysis include the following:

- The sensitivity analysis will be conducted for each operational condition of interest
- For each operational condition of interest, different truck platoon performance measures would be evaluated. These include:
    - Average travel time
    - Average speed
    - Average vehicle throughput
    - Fuel economy
    - Emissions

After the sensitivity analyses is completed, the IE would draw general conclusions on how changes in truck platoon penetration rate impacts truck platoon benefits. In addition, a general conclusion would be drawn on operational conditions under which truck platoon is more likely to be beneficial.

# 4 Expanded Geographical Analysis

This chapter describes the analysis approach that the IE will use to extend the impacts/benefits of truck platooning from the FOT to the regional and national levels (22). The expanded geographic analysis will help to quantify the nature and proportion of regional and national freight transportation that may potentially benefit from truck platooning as would be deployed in the Phase 2 FOT and assess the extent of potential impacts/benefits accrued.

Figure 3 below is a graphical representation that highlights the steps in the analysis approach that the IE will follow in extending the impacts/benefits of the truck platooning FOT to the regional and national levels.

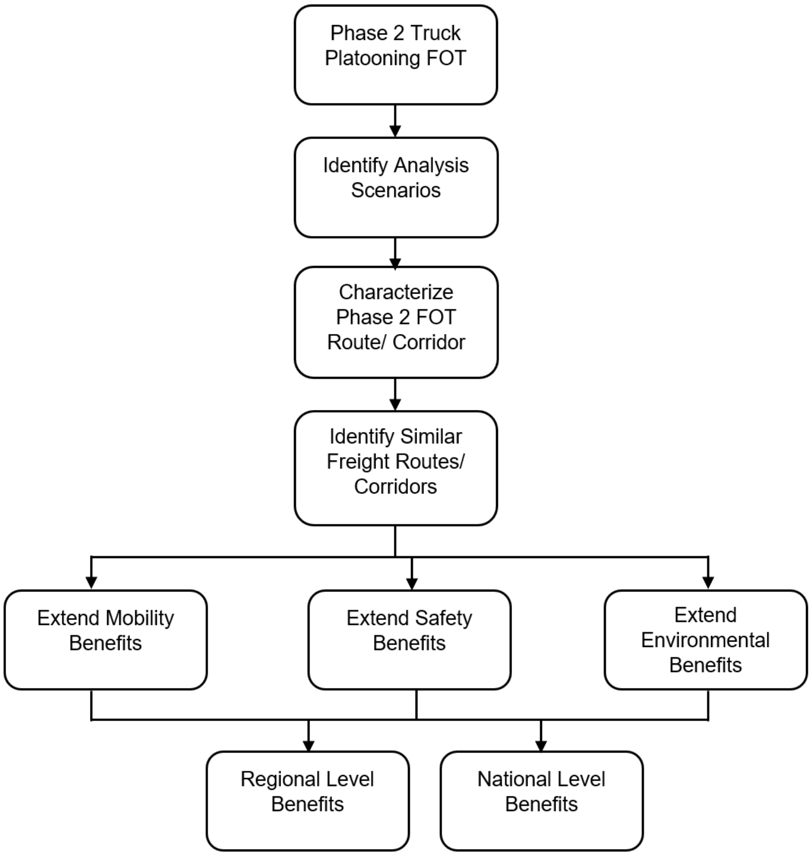


**Figure 3. Analysis Approach for Extending Truck Platooning Benefits Beyond FOT (Source: Noblis)**

It is important to note that the approach presented in Figure 3 can also be used to extend benefits obtained from the simulation modeling process to regional and national levels.

## 4.1 Identify Analysis Scenarios

The IE will use data collected during the FOT, in combination with traffic data (e.g., volume), weather data (e.g., precipitation intensity), and other operational data from the FOT route to identify analysis scenarios (i.e., operational conditions) based on which the expanded analyses will be conducted. Trucks equipped with platooning technology are expected to produce safety, operational, and economic benefits; however, these potential benefits may not always be experienced during active platoon engagements. It is anticipated that different benefits will accrue under different operational conditions. For example, high traffic demand levels on segments of the FOT route may necessitate the need to disengage platooning at such locations. However, if active platooning is maintained in high demand levels, it is possible that the magnitude of benefits during such conditions will be different from the magnitude of benefits when trucks platoon in low traffic demand conditions. For example, aerodynamic drag and related fuel savings are magnified at higher speeds. As a result of the potential variability in benefits due to changing travel conditions, there is a need to identify and understand the variety of scenarios in which truck platooning FOT produced benefits. It is important to note that the FOT route may not cover all potential analysis scenarios for truck platoons. However, future studies may build on the analysis scenarios that would be identified in this project.

Identifying analysis scenarios for the expanded geographic analyses has three key uses. Firstly, it enables the identification of key attributes of operational conditions (e.g., traffic flow characteristics, time of day, weather, etc.) under which truck platooning is most beneficial. These key attributes will help characterize the FOT corridor based on which freight corridors in the nation with similar attributes as the FOT corridor would be identified. Secondly, knowing the operational conditions under which truck platooning is most beneficial will prevent wholesale extrapolation of benefits, ensuring that extrapolation is done only for freight corridors with similar operational conditions. Lastly, this will help to determine the proportion of regional and nationwide truck freight travel that will benefit from truck platooning technology as deployed in the FOT. It is important to note that the National Renewable Energy Laboratory (NREL) published a study that estimated the total miles of truck travel that are technically suitable for platooning (20). However, this study used data from trucks that were not engaged in any type of platooning. Hence, the estimates to be generated in the expanded analysis would be different and very insightful.

### Process for Identifying Analysis Scenarios

Cluster analysis would be used to identify the different operational conditions that would be experienced by platoon trucks during the FOT. Clustering refers to a very broad set of techniques for finding subgroups, or clusters, in a dataset (8). These techniques include the following:

- **K-Means Clustering:** This technique partitions a dataset into K distinct non-overlapping clusters. To perform K-means clustering, the desired number of clusters K must be specified; then the K-means algorithm will assign each observation to exactly one of the K clusters (9). In practice the number of clusters K is varied until the one with most useful or interpretable solution is selected. The K-means algorithm is one of the simplest clustering algorithms, but it is computationally difficult. Some of the drawbacks include (7):
    - An inappropriate choice of K may yield poor results
    - Convergence to a local minimum may produce counterintuitive results
    - The clustering algorithm is such that all data, including outliers, are assigned to a cluster.

- **Hierarchical Clustering:** This approach involves building a hierarchy of clusters using a bottom-up (agglomerative) or top-down (divisive) technique. In agglomerative clustering, each datapoint is initially treated as its own cluster; then, the algorithm proceeds iteratively to merge clusters that are similar (based on a dissimilarity measure) until there is only one cluster (7). In divisive clustering, all observations start off in one cluster, and clusters are successively split until each cluster has only one observation. The advantage of the hierarchical clustering is that the number of clusters do not need to be pre-defined. The user can determine when to stop based on a pre-defined stopping criterion. The disadvantage is that it is time consuming (7).
- **Expectation Maximization Clustering:** This technique extends the K-means clustering algorithm by computing probabilities of cluster memberships based on one or more probability distributions. The goal is to maximize the probability that the data falls into the clusters created. The main advantage of the expected maximization algorithm is that it is robust to noisy data. It can cluster data even when incomplete. The main disadvantage is that it converges very slowly (7).

For details on how to conduct clustering, consult *Traffic Analysis Toolbox Volume III: 2019 Update to the 2004 Version* (7). Examples of statistical and data mining tools that offer clustering capability include commercial tools such as MATLAB, IBM SPSS, SAS and open source software such as WEKA and GNU Octave.

Table 1 below provides a list of FOT corridor attribute data needed for identifying operational conditions using cluster analysis.

**Table 1. List of Potential Data for Conducting Cluster Analysis**

| Data | Source |
|---|---|
| Demand (e.g., volume, traffic density) | FOT corridor transportation agencies |
| Weather (e.g., precipitation levels, visibility, wind speed etc.) | FOT corridor transportation agencies, National Transportation Agencies (See Section 4.2.3) |
| Incident (e.g., number of lanes blocked, severity, etc.) | FOT corridor transportation agencies |
| Travel Time | FOT corridor transportation agencies |
| Traffic Mix (% of passenger vehicles, % of trucks) | FOT corridor transportation agencies |
| Bottleneck Throughput (if any) | FOT corridor transportation agencies |

Considering the length of the FOT corridor (about 1,400 miles), it is not practical to collect data for its entire length. The locations for collecting these data elements should be guided by the results of PATH's assessment of the FOT. As part of their assessment, PATH will calculate the performance measure "percentage of highway driving time/distance spent in platooning mode" and categorize by location. This performance measure should provide information on where test trucks were engaged in active platooning. Since the benefits of truck platooning can only be experienced when trucks travel in "platoon mode," data for conducting the cluster analysis should be collected for only those locations where active platooning consistently occurs. In addition, PATH will categorize this performance measure by weather conditions and traffic density. Results of these categorizations should inform whether traffic density and weather conditions are critical to identifying operational conditions.

The cluster analysis would result in distinct clusters representing the different operational conditions in the FOT corridor. Each cluster or operational condition will contain individual days and corresponding time-stamped attributes. For example, a cluster may contain a specific day such as January 10, 2022, and corresponding time-stamped attributes such as volumes, travel times, precipitation levels in 15-minutes, 30-minutes, or hourly time intervals. When operational conditions identified by cluster analysis are matched with time-stamped truck platoon data (e.g., time-stamped GPS data), it will provide insights on which operational conditions produce most truck platooning benefits.

## 4.2 Characterize Phase 2 FOT Route/Corridor

The Phase 2 FOT corridor has inherent attributes. In order to identify similar freight corridors to which truck platooning benefits may be extrapolated, these attributes should be identified and then used to characterize the FOT corridor. Essentially, the characterization becomes a criterion (defined by attributes and corresponding values) for screening potential freight corridors that would be used in the expanded geographic analysis. At a minimum, the FOT corridor should be characterized based on the following attribute categories: vehicle population, road geometry and network characteristics, operational conditions (weather and demand should be treated separately), and transportation issues in the corridor. The list of attributes to be used in the characterization should be finalized after reviewing results of PATH's FOT assessment, which will provide useful information on which attributes really influence truck platoon performance. Table 2 below provides a list of attribute categories and corresponding attributes that should be considered when characterizing the FOT route.

**Table 2. Preliminary Attributes for FOT Route Characterization**

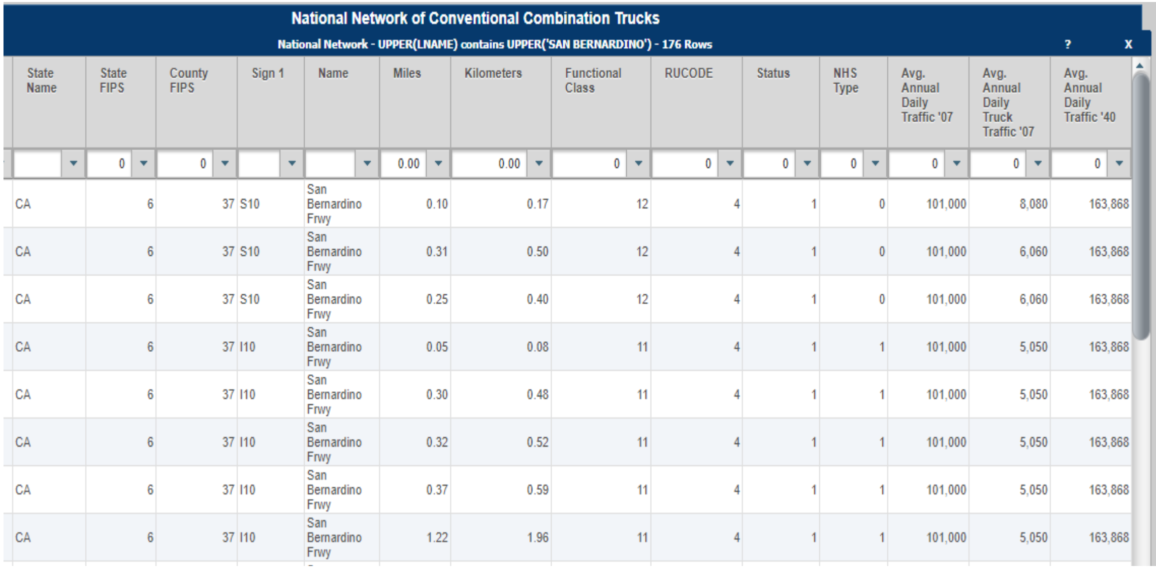
| Attribute Category | Attributes |
|---|---|
| Vehicle Population | • Percentage of passenger vehicles<br>• Percentage of long-distance interstate trucks |
| Road Geometry and Network Characteristics | • Roadway vertical/ horizontal alignment<br>• Rural/Urban interstate<br>• Driving speeds<br>• Lane configurations<br>• Lane restrictions<br>• Entry/Exit ramp density<br>• Work zones |
| Operational Conditions – Weather | • Snow and ice (not likely)<br>• Precipitation levels and intensity<br>• Wind gust/ speeds<br>• Visibility levels |
| Operational Conditions – Demand | • Annual Average Daily Traffic (AADT), Volumes<br>• Corridor VMT (trucks and passenger vehicles)<br>• Corridor hours of delay |
| Corridor Transportation Issues | • Crash statistics |

## Data Sources

Data for characterizing the FOT corridor would be collected by the IE from appropriate sources. The sections below describe potential sources of data needed for characterizing the FOT corridor and identifying freight corridors with similar attributes.

### *Vehicle Population Data*

The main source of data for characterizing vehicle population in the FOT corridor is the respective state DOTs (California DOT, Arizona DOT, New Mexico DOT, and Texas DOT) that manage the interstates in the FOT corridor. Vehicle population data for other freight routes in the nation can be found from state DOTs and FHWA policy information statistics. For example, a FHWA GIS application (HEPGIS) has relevant information on AADT and Annual Average Daily Truck Traffic (AADTT) (10). Figure 3 below shows AADT and AADTT for sections of I-10 (i.e., San Bernardino Freeway) around Rancho Cucamonga, where Roly's Trucking's main terminal is located.



National Network of Conventional Combination Trucks

National Network - UPPER(LNAME) contains UPPER('SAN BERNARDINO') - 176 Rows

| State Name | State FIPS | County FIPS | Sign 1 | Name | Miles | Kilometers | Functional Class | RUCODE | Status | NHS Type | Avg. Annual Daily Traffic '07 | Avg. Annual Daily Truck Traffic '07 | Avg. Annual Daily Traffic '40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | | | 0.00 | 0.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CA | 6 | 37 | S10 | San Bernardino Frwy | 0.10 | 0.17 | 12 | 4 | 1 | 0 | 101,000 | 8,080 | 163,868 |
| CA | 6 | 37 | S10 | San Bernardino Frwy | 0.31 | 0.50 | 12 | 4 | 1 | 0 | 101,000 | 6,060 | 163,868 |
| CA | 6 | 37 | S10 | San Bernardino Frwy | 0.25 | 0.40 | 12 | 4 | 1 | 0 | 101,000 | 6,060 | 163,868 |
| CA | 6 | 37 | I10 | San Bernardino Frwy | 0.05 | 0.08 | 11 | 4 | 1 | 1 | 101,000 | 5,050 | 163,868 |
| CA | 6 | 37 | I10 | San Bernardino Frwy | 0.30 | 0.48 | 11 | 4 | 1 | 1 | 101,000 | 5,050 | 163,868 |
| CA | 6 | 37 | I10 | San Bernardino Frwy | 0.32 | 0.52 | 11 | 4 | 1 | 1 | 101,000 | 5,050 | 163,868 |
| CA | 6 | 37 | I10 | San Bernardino Frwy | 0.37 | 0.59 | 11 | 4 | 1 | 1 | 101,000 | 5,050 | 163,868 |
| CA | 6 | 37 | I10 | San Bernardino Frwy | 1.22 | 1.96 | 11 | 4 | 1 | 1 | 101,000 | 5,050 | 163,868 |

**Figure 4. Vehicle Population Data: Example for I-10 Freeway (Source: FHWA)**

## Road Geometry and Network Characteristics and Operational Conditions – Demand

Data on road geometry, network characteristics, and demand levels can be found from state DOTs, FHWA data reporting systems, Bureau of Transportation Statistics (BTS), and private sector sources. Table 3 below provides links to some of the publicly available road infrastructure and network characteristics data. It is important to note that some of the publicly available data may be a little dated; however, they provide useful information for starting the expanded analyses. In addition, the IE will have to contact appropriate state DOTs and FHWA programs, and private sector sources for most current data.

**Table 3. Road Geometry, Network Characteristics and Demand Data Sources**

| Data Type | Data Source |
|---|---|
| Highway Performance Monitoring System (HPMS) - FHWA | https://www.fhwa.dot.gov/policyinformation/hpms.cfm. |
| All Road Network of Linear Referenced Data (ARNOLD) | https://www.fhwa.dot.gov/policyinformation/hpms/documents/arnold_reference_manual_2014.pdf. |
| Freight Analysis Framework (FAF) | https://www.bts.gov/faf. |

| Data Type | Data Source |
|---|---|
| FAF Flows by Metro Regions - FHWA | https://hepgis.fhwa.dot.gov/fhwagis/ViewMap.aspx?map=FAF4\|FAF4+Metro+Region+Map&form=metro. |
| Long Distance Truck Network Flow - FHWA | https://hepgis.fhwa.dot.gov/fhwagis/ViewMap.aspx?map=Freight%20Analysis%7C2045%20FAF4%20Long%20Distance%20Truck%20Network%20Flow. |
| Annual Roadway Congestion Index - BTS | https://www.bts.gov/content/annual-roadway-congestion-index. |
| Travel Monitoring and Traffic Volume - FHWA | https://www.fhwa.dot.gov/policyinformation/travelmonitoring.cfm. |
| VMT Data – STREETLIGHT DATA | https://www.streetlightdata.com/vmt-monitor-by-county/#emergency-map-response. |

## Operational Condition – Weather

Weather data can be obtained from state and national agencies. Some state DOTs have Road Weather Programs; such states instrument their interstates with appropriate weather sensors to collect needed weather data. The IE would contact California, Arizona and Texas DOTs for weather data along I-10 and I-20. The National Oceanic and Atmospheric Administration (NOAA) provides weather information across the entire nation. NOAA has various divisions that provides different types of weather information that will be pertinent to this analysis. For example, NOAA's National Center for Environmental Information (https://www.ncdc.noaa.gov/climateatlas/.) provides information on precipitation and temperature (11). Similarly, NOAA's National Weather Service (https://www.weather.gov/cys/unitedstatesroadconditions.) compiles information on road conditions across the nation (12). The Department of Energy (DOE) also compiles information about wind speeds across the nation (https://windexchange.energy.gov/maps-data?height=100m.) (13). Since the FOT corridor is in the southern part of the nation, snow and ice are not expected to impact operational conditions in the corridor.

## Corridor Transportation Issues

Data on corridor transportation issues can be obtained from state and national sources. Transportation issues refer to any phenomenon that affects traffic operations in the corridor. Traffic safety is often the biggest issue for most transportation corridors. In addition to obtaining safety data from state DOTs, national agencies such as National Highway Traffic Safety Administration (NHTSA), FHWA and BTS are key sources of safety data. These include NHTSA's Query Tool (https://cdan.dot.gov/query) (14) and Traffic Safety Annual Tables (https://cdan.nhtsa.gov/tsftables/tsfar.htm#) (15); and FHWA's Road Safety Dashboard (https://rspcb.safety.fhwa.dot.gov/Dashboard/Default.aspx) (16).

## Down Selecting Attributes

Characterizing the FOT corridor may start with many attributes. However, not all of the initial list of attributes will be used to characterize the FOT corridor. Many reasons may contribute to the inclusion/exclusion of attributes into the final set. These reasons and the process for down selecting attributes are discussed below (22).

### *Attribute Relatability*

This involves assessing the usefulness of FOT corridor attributes to the specific objective of assessing the benefits of truck platooning. For example, the FOT corridor may have an attribute such as the number of truck parking lots. While this is an important attribute for a freight corridor in general, it does not influence truck platoon operation or its impacts assessment. Consequently, number of truck parking lots may be expected to have a very low relatability for the FOT corridor's truck platooning deployment and evaluation. It is recommended that relatability ratings are assigned to all identified FOT corridor attributes. The following relatability rating scale (as shown in Table 4) can be used to assign relatability scores to attributes.

**Table 4. Attribute Relatability Rating Scale**

| Relatability Rating | Value | Interpretation |
|---|---|---|
| Very Low | 1 | No direct relatability to project goal |
| Low | 2 | Low relatability/usefulness to project goal |
| Moderate | 3 | Somewhat relates or useful to project goal |
| High | 4 | Mostly relates/useful to project goal |
| Very High | 5 | Directly relates/useful to project goal |

Assigning relatability ratings to attributes is a critical step. If done poorly, wrong attributes with less direct effect on truck platooning will be selected and used for identifying similar freight corridors. This will lead to inaccurate extrapolation of truck platooning benefits beyond the physical boundaries of the FOT corridor. Therefore, it is recommended that findings from PATH's FOT assessment be used to guide selection of the key attributes.

***Attribute Data Availability/Accessibility***

Availability of data is critical to the characterization of the FOT corridor. Although a corridor attribute may have a high relatability score, if data for this attribute is not available, then it cannot be used in the characterization process. Similarly, if attribute data exists but not accessible to the IE, then it cannot be used in the characterization process. The ultimate desire is for attribute data to be readily available and accessible. It is recommended that availability/accessibility scores are assigned to all identified FOT corridor attributes. The availability/accessibility rating scale (as shown in Table 5) can be used to assign availability/accessibility scores to attributes.

**Table 5. Attribute Availability/Accessibility Rating Scale**

| Availability/Accessibility Rating | Value | Interpretation |
|---|---|---|
| Very Low | 1 | No database found for attribute |
| Low | 2 | Some database exists but not uniform across states/ locations |
| Medium | 3 | Data is available but requires extensive processing |
| High | 4 | Databases available and accessible, nationwide |
| Very High | 5 | Databases available and easily accessible |

## Attribute Rating Matrix

After assigning relatability and data availability/accessibility scores to attributes, the product of both scores will generate an overall attribute rating. The overall attribute rating will be used to identify:

- **Very Critical Attributes:** These are key attributes required for characterizing FOT corridor and identifying similar freight corridors. Values in this category can range from 18–25.
- **Moderately Critical Attributes:** These are possible key attributes that can be used to characterize FOT corridor as well as identify similar freight corridors. However, there is some difficulty with data availability/accessibility. Values range from 10–17.
- **Somewhat Critical Attributes:** These attributes have low relatability to the project goal but have high data availability/accessibility. Values range from 5–9.
- **Not Critical:** These attributes have very low relatability to project goal as well as very low data availability/accessibility. Values range from 1–4.

The range of overall attribute ratings is displayed as a heatmap in Table 6 below.

**Table 6: Attribute Rating Matrix (Source: TTI)**

| Attributes Heat Map | Very Low Relatability (1) | Low Relatability (2) | Medium Relatability (3) | High Relatability (4) | Very High Relatability (5) |
|---|---|---|---|---|---|
| **Very High Availability (5)** | 5 = Somewhat Critical | 10 = Moderately Critical | 15 = Moderately Critical | 20 = Very Critical | 25 = Very Critical |
| **High Availability (4)** | 4 = Not Critical | 8 = Somewhat Critical | 12 = Moderately Critical | 16 = Moderately Critical | 20 = Very Critical |
| **Medium Availability (3)** | 3 = Not Critical | 6 = Somewhat Critical | 9 = Somewhat Critical | 12 = Moderately Critical | 15 = Moderately Critical |
| **Low Availability (2)** | 2 = Not Critical | 4 = Not Critical | 6 = Somewhat Critical | 8 = Somewhat Critical | 10 = Moderately Critical |
| **Very Low Availability (1)** | 1 = Not Critical | 2 = Not Critical | 3 = Not Critical | 4 = Not Critical | 5 = Somewhat Critical |

It is recommended that only very critical and moderately critical attributes should be used to characterize the FOT corridor.

## 4.3 Identify Similar Freight Corridors

Identifying key attributes for the FOT corridor sets the stage for identifying freight corridors that have similar attributes. Two statistical techniques have often been mentioned in the literature for achieving this task: cluster analysis and K-Nearest Neighbor (KNN) model. However, cluster analysis has been found not to be suitable for this kind of task due to issues regarding over-sensitivity, outliers, arbitrary cluster sizes, resulting cluster sizes being too small and needing to force minimum cluster sizes, excluding variables, etc. (17). Cluster analysis is more suitable for situations where we want to discover structure (i.e., distinct clusters or subgroups) in a dataset. On the other hand, when there is a specific structure (i.e., FOT corridor attributes) to be compared with other datasets, the KNN approach is more appropriate and has been found to generate useful results (17). Hence, the KNN method will be used to identify the similar freight corridors.

## K- Nearest Neighbor Model

The KNN model classifies observations (i.e., attributes) into classes by assigning each observation to the class most common among that observation's K nearest neighbors using a distance function (mostly the Euclidean distance). Given a test observation, the KNN classifier first identifies the K points in the data that are closest to the observation, then computes the conditional probabilities for all the different classes that the K nearest points belong to. Next, the KNN classifier applies Bayes rule to classify the test observation to the class which has the largest probability. K is a user-defined parameter which defines how flexible the decision boundary is. A smaller K results in an overly flexible decision boundary while a large K leads to a not sufficiently flexible decision boundary. Choosing the correct value for K is critical to the accurate identification of sites that are similar to the FOT corridor.

To apply the KNN approach to identify freight corridors that have similar attributes as the FOT corridor:

- The key attributes used to characterize the FOT corridor must be normalized. For example, AADT and functional classification of an interstate have different scales (100s of thousands and single digit respectively). Normalization ensures that all the attributes have a common scale and that no single attribute dominates the others. The appropriate normalization technique must be used.
- Since each of the key attributes used to characterize FOT route have different impacts on truck platooning, each attribute must be assigned a weight according to its significance.
- The KNN algorithm will use the appropriate distance function to calculate the similarity or dissimilarity between attribute categories of the FOT corridor and potential similar freight corridors. An example of the distance function used by KNN is the Lebesgue Space Normalized Euclidean Distance shown in equation 2.

$$d = \sqrt{\sum_{i=1}^{a}[w_i\left(\frac{v_{xi}-v_{0i}}{v_{0i}}\right)]^2} \quad \text{(Eq. 2.)}$$

  Where:
    - $d$ = Normalized, weighted, Euclidean distance, or the dissimilarity measure
    - $a$ = Attributes
    - $w$ = Weighting factor
    - $i$ = $i^{th}$ attribute
    - $v$ = Attribute value for FOT corridor 0 or potential similar freight corridor x
- Since $d$ is a dissimilarity measure, its inverse $d^{-1}$ is a measure of similarity.
- The total similarity score for each potential similar freight corridor is obtained by summing the similarity scores for all the attribute categories. Freight corridors that have high similarity values will be identified as similar to the FOT freight corridor and vice versa.

For example, consider these network characteristics and operational condition attributes for the FOT corridor and three potential similar freight corridors.

**Table 7. Illustrative Similarity Comparison between FOT Corridor and Hypothetical Freight Corridors**

| Measure | FOT Corridor | A | B | C |
|---|---|---|---|---|
| **AADTT** | 8,080 | 4,000 | 7,950 | 11,250 |
| **Congestion Index** | 0.7 | 1.2 | 0.8 | 0.3 |

| | | | | |
|---|---|---|---|---|
| **% Trucks** | 25 | 13 | 22 | 41 |
| **VMT Total** | 1,040 | 3,750 | 1,010 | 2,120 |
| **d** | (zero) | 0.171 | 0.064 | 0.294 |
| **Similarity ($d^{-1}$)** | (infinite) | 5.85 | **15.63** | 3.40 |

From the similarity measures in Table 7 above, freight corridor B is more similar to the FOT freight corridor than freight corridors A and C. The KNN model will identify freight corridors that are similar to the FOT corridor using the same approach.

The IE would define the criteria for selecting the final set of similar freight corridors after the KNN model has generated similarity measures for all the candidate freight corridors. For example, the IE may decide to set a similarity measure threshold and include only freight corridors whose similarity measures are higher than the threshold. In addition, consideration may be given to having a specified number of similar freight corridors (e.g., top 20 similar freight corridors). The IE would consult with USDOT to finalize the criteria for selecting the final list of similar freight corridors.

## 4.4 Extend Truck Platooning Impacts/Benefits

Extrapolating observed truck platooning benefits to identified similar freight corridors is a very critical component of the expanded geographic analysis. It provides additional insights on the benefits that would have been accrued if the truck platooning technology (as deployed in the FOT) was deployed in those similar freight corridors and provides the basis for scaling up the benefits to a larger geographic level (i.e., state, regional and national levels). The next sections discuss the general approach for extending truck platooning benefits as well as how to do it for the different types of truck platooning benefits (i.e., safety, mobility, environmental, fleet operator).

### General Approach for Extending Truck Platooning Benefits

The following steps describe general process for extending truck platooning benefits to larger geographic extent beyond the physical boundary of the Phase 2 FOT corridor.

- **Step 1:** In sections 4.1 and 4.1.1, the importance and process for identifying analysis scenarios (i.e., operational conditions) were discussed. These analysis scenarios described the different operating conditions (identified based on weather, demand, FOT corridor network characteristics, etc.) along the FOT corridor under which truck platooning benefits were experienced. Each operational condition identified through the cluster analysis has unique attributes. These attributes would be used to identify similar operational conditions in the similar freight corridors. For example, if operational condition 1 in the FOT corridor has an average volume of 500 vehicle per hour, visibility is beyond 1 mile, precipitation intensity of 0, 5% of trucks in the traffic mix, and 3 lanes in the direction of travel, these thresholds would be used to identify a similar operating condition in the similar freight corridors. Do this for all the different operational conditions identified through the cluster analysis.
- **Step 2:** For each operational condition identified for the FOT corridor, calculate the total miles traveled by platoon trucks while engaged in active platooning. This can be accomplished by matching truck platooning data such as time-stamped GPS data with the different operational conditions to determine the active platooning distances experienced in each operational condition. Each operational condition also has time-stamped attributes such as time-stamped volumes, precipitation intensity, visibility, and others. Therefore, "time" becomes a common

feature that enables different datasets to be merged. The same approach can also be used to calculate the total hours of travel experienced by platoon trucks while operating in active mode for each operational condition. For example, the total miles of active platooning experienced for FOT operational condition 1 using this approach can be estimated to be 4000 miles.

- **Step 3.** Calculate total truck platooning benefits for each operational condition. PATH's FOT assessment will calculate truck platooning performance measures for the entire FOT and sort them based on gap settings (e.g., changes in fuel use sorted by gaps), truck position in a platoon (e.g., changes in emission levels sorted by truck position in platoon), weather (e.g., crashes and safety-critical conflicts sorted by weather), etc. The truck platooning benefits will not be sorted according to the different operational conditions. Therefore, the IE would have to distribute the total truck platooning benefits calculated by PATH across the different operational conditions. Since both operational condition attributes and truck platooning data are time-stamped, these two datasets can be merged to calculate truck platooning benefits for each operational condition. For example, if 40,000 gallons of total fuel savings was obtained in the FOT, this can be distributed across the different operational conditions such as 20,000 gallons of fuel savings for operational condition 1, compared with 13,000 gallons and 7,000 gallons of fuel savings for operational conditions 2 and 3 respectively.
- **Step 4:** Express the different truck platoon benefits experienced in the FOT corridor for each operational condition as a ratio of the total miles of active platooning in that operational condition. For example, if the total fuel savings experienced under operational condition 1 is 20,000 gallons, and the corresponding total miles of active platooning is 40,000 miles; then, the average fuel savings for operational condition 1 will be 0.5 gallons per mile. This can be done for safety benefits (i.e., crash reductions/mile), mobility (travel time savings per mile, corridor throughput increases per mile), and others.
- **Step 5:** For each operational condition identified for a similar freight corridor using the approach described in step 1, calculate the total miles of platooning that would have occurred if truck platooning (same as what was deployed in FOT corridor) were to be deployed in that freight corridor. The operating conditions identified for the similar freight corridors would have both time and location attributes. For example, the attributes of operational condition 1 which was identified for the FOT corridor will be used to identify a similar operational condition in a similar freight corridor. The segments along the similar freight corridor where this similar operational condition occurs may include from Mile Marker (MM) 10 to MM 20, MM 40 to MM 50, and MM 100 to MM 115. This implies that the similar operational condition occurs along a total segment of 35 miles. For each truck platooning trip along the similar freight corridor, platoon trucks will be expected to platoon whenever they travel through these segments identified for the operational condition. PATH's Phase 2 Proposal estimates between 50 – 200 one-way truck platoon trips during the one-year FOT. Assuming a total of 125 one-way truck platoon trips will occur on this similar freight corridor; then, the total miles of active platooning within the 35-mile segment will be 35 * 125 which equals 4,375 miles.
- **Step 6:** In this step, apply the benefits experienced for each FOT operational condition to the corresponding similar operational conditions in the similar freight corridors. This is achieved by multiplying the unit benefits for each FOT operational condition (obtained in step 4) by the total miles of potential active platooning (obtained in step 5) that would be experienced in the corresponding similar operational conditions in the similar freight corridors. For example, if the unit fuel savings for operational condition 1 is 2.5 gallons per mile, and the total miles of potential active platooning for a similar operational condition is 4,375 miles, then:

*Total fuel savings for the similar operational condition = 0.5 * 4375 = 2,187 gallons*

This approach can be used to estimate potential truck platooning benefits for all the different benefit categories (i.e., safety, mobility and environmental). It is important to note that an adjustment factor could be applied to the estimated 2,188 gallons of fuel savings for the similar operational condition to account for the magnitude of similarity between the FOT corridor and the similar freight corridor. Methodologies for generating these adjustment factors will be discussed in section 4.4.2.

- **Step 7:** For each similar freight corridor, sum up the extended benefits for all operational conditions similar to that of the FOT corridor. The summation should be done separately for each truck platooning benefit area. For example, for a similar freight corridor ($FC_s$) with three corresponding similar operational conditions, sum up separately the mobility, safety, environmental, and fleet operator benefits across the three operational conditions. Equation 3 below shows the summation of safety benefits for a similar freight corridor across the three operational conditions. The same can be done for all the truck platooning benefit areas.

$$FC_s\,(Safety\ Benefits) = \sum_{oc1}^{oc3}(Safety\ Benefits) \quad \text{(Eq. 3.)}$$

Where:
$FC_s$ = Similar freight corridor
OC1 = Operational condition 1
OC3 = Operational condition 3

Then, sum up the total extended benefits for all similar freight corridors across the individual truck platooning benefit areas (i.e., safety, mobility, environmental and fleet operator) to obtain regional (assuming some similar freight corridors are within the same region) and national level benefits.

## Apportioning Truck Platooning Benefits to Similar Freight Corridors

When extending truck platooning benefits from the FOT corridor to similar freight corridors, an important issue regarding whether to do a "wholesale" transfer of benefits should be addressed. For example, if the FOT corridor's operational condition 1 has an average fuel savings of 0.5 gallons per mile, should a similar operational condition in a similar freight corridor be assigned fuel savings of 0.5 gallons per mile when extending benefits to this similar freight corridor? Potential approaches for addressing this issue are discussed below.

### *Approach 1: Wholesale Transfer of Benefits*

This approach assumes that the FOT corridor and the similar freight corridors are exactly the same in attributes and operational conditions. That is, there is a 1:1 mapping between the FOT corridor and similar freight corridors. Hence, the transfer of benefits to similar freight corridors is done in a "wholesale" fashion without adjusting for any differences between the freight corridors. Theoretically, this assumption cannot be true since no two freight corridors or operational conditions can be exactly the same. There will always be some differences between the attributes and operational conditions of the FOT corridor and similar freight corridors. However, in practical terms, if the magnitude of the differences between the FOT corridor and a similar freight corridor is very small, then the assumption that they are exactly the same can hold. This allows for a “wholesale” transfer of benefits from the FOT corridor to that similar freight corridor.

As an example, if the FOT corridor’s operational condition 1 has average fuel savings of 0.5 gallons per mile, then a similar operational condition in a similar freight corridor can be assigned the whole fuel savings of 0.5 gallons per mile in this approach.

***Approach 2: Use of Similarity Measures to Account for Differences***

This approach uses the similarity measures obtained from the KNN model to proportionally assign truck platooning benefits to similar freight corridors. Let’s assume three freight corridors have been identified as having similar attributes as the FOT corridor using the KNN model. Table 8 below shows the attributes of the three hypothetical similar freight corridors and their similarity measures obtained using Equation 2. From Table 8, it is apparent that hypothetical freight corridor B is most similar to the FOT corridor based on the similarity measure of 90.91%. That is, there is 90.91% similarity between the attributes of the FOT corridor and hypothetical freight corridor B. This implies that, when extending truck platooning benefits, hypothetical corridor B would receive only 90.91% of the actual benefit experienced in the FOT corridor. The same interpretations can be given to the similarity measures for hypothetical corridors A and C. In instances where a corridor has less similarity to the FOT corridor but has attributes that are more conducive for truck platooning than the FOT corridor, the transferred benefit based on the similarity score can be considered as the minimum truck platooning benefit.

Let’s assume the FOT corridor’s operational condition 1 experienced average fuel savings of 0.5 gallons per mile. For illustration purposes, let’s also assume that hypothetical freight corridors A, B, and C have operational conditions that are similar to operational condition 1 in the FOT corridor.

**Table 8. Hypothetical Similar Freight Corridors and Corresponding Similarity Measures**

| Measure | FOT Corridor | A | B | C |
|---|---|---|---|---|
| **AADTT** | 8,080 | 4,000 | 7,950 | 11,250 |
| **Congestion Index** | 0.7 | 1.2 | 0.6 | 0.95 |
| **% Trucks** | 25 | 13 | 22 | 17 |
| **VMT Total** | 1,040 | 3,750 | 1,570 | 712 |
| **d** | (zero) | 0.019 | 0.011 | 0.014 |
| **Similarity ($d^{-1}$)** | (infinite) | 52.63% | 90.91% | 71.43% |

If the total miles of active truck platooning for each of the similar operational conditions in the similar hypothetical freight corridors is 4,375 miles, then the total fuel savings for each of them would as shown below:

*Hypothetical Corridor A = 52.63% * 0.5 * 4,375 = 1,151.2 gallons*
*Hypothetical Corridor B = 90.91% * 0.5 * 4,375 = 1,988.7 gallons*
*Hypothetical Corridor C = 71.43% * 0.5 * 4,375 = 1,562.5 gallons*

As shown in the example above, this approach uses the similarity measures calculated for each hypothetical freight corridor to adjust the magnitude of the truck platooning benefits that will be extended to similar freight corridors.

### *Approach 3: Use of Regression Model to Account for Differences*

In this approach a regression model is developed to capture how truck platooning benefits (e.g., fuel savings) vary with FOT corridor attributes (e.g., volume, weather, grade, etc.). The regression model is then used to estimate truck platooning benefits for similar freight corridors and corresponding operational conditions. If regression models are used to extend benefits to similar freight corridors, they will indirectly account for differences between the FOT corridor and similar freight corridors. This is because, the regression coefficients are estimated using the exact values of FOT corridor attributes. Therefore, if the attribute values of a similar freight corridor are different from that of the FOT corridor, the regression model's predicted truck platoon platooning benefits for the similar freight corridor will also be different. This approach is more suitable if there is adequate data to develop accurate regression models that explain adequately, the variability in the dataset.

When this approach is used, it is important to include total miles of active truck platooning as an explanatory variable in the regression model to control for potential differences between the lengths of FOT corridor and similar freight corridors. In addition, the choice of regression model approach (i.e., simple regression vs logistic regression) will depend on the nature of attributes (i.e., quantitative attributes vs categorical attributes).

# 5 Supplementary Analysis

This chapter discusses additional analyses to be conducted regarding the impacts of truck platoons. This discussion focuses on truck platoon impact areas of interest not covered in PATH's FOT evaluation.

## 5.1 Truck Platoon Impacts on Surrounding Vehicle Behavior

The interactions between truck platoons and regular passenger vehicles are very critical and contribute significantly to the impacts of truck platoons on traffic safety and mobility. Although truck platooning is expected to impact the tactical maneuvers of surrounding vehicles, the nature and magnitude of the impacts is not well studied using field data. Most of the current work on this topic involves the use of driver simulators to study the impacts of truck platoons on surrounding vehicle behavior (18). The FOT will instrument platoon trucks with side-mounted video cameras and lidars to capture information about target objects in adjacent lanes on both sides enabling recording of truck speed, target lane object speeds and locations. However, PATH will not process or analyze the collected data.

The IE would explore various methodologies to process and extract relevant information on surrounding vehicle behavior. The methodologies to be explored would range from fully automated machine-learning based video extraction techniques such as 3D Convolution Neural Networks (3D ConvNet) (19) to hybrid techniques that uses both machine and human assistance to extract and process video data. Key information on surrounding vehicle driving behavior that would be extracted from the video and lidar data include:

- Lane choice selection
- Lane changing behavior
- Speed behavior
- Merging behavior
- Adjacent lane utilization
- Cut-in and cut-out behavior

The IE would leverage this information to augment the simulation model developed in Chapter 3 for subsequent use in sensitivity analysis and other truck platoon impact areas such as mobility. The IE would also investigate if there is a need to develop different behavioral models for surrounding vehicles based on different operational conditions.

## 5.2 Truck Platoon Impacts on Traffic Flow

Using the simulation model developed in Chapter 3, the IE would conduct additional investigation on the impacts of truck platoons on traffic flow. The analysis would be conducted for different operational conditions (e.g., high traffic demand vs. low traffic demand) so that the full range of truck platoon impacts on traffic flow can be established. Where possible, traffic flow performance would be measured at the corridor level as well as vehicle type level (e.g., average travel time of platoon trucks). Performance measures that would be utilized for this assessment include:

- Average travel time
- Travel time reliability
- Average speed
- Vehicle throughput

The analysis would also consider the impacts of platoon truck market penetration on traffic flow.

## 5.3 Truck Platoon Impacts on Pavements and Bridges

The impacts of truck platoons on roadway pavements and bridge structures will not be covered in PATH's FOT analysis. However, PATH will collect some of the data needed for such analysis including truck weight and loading data and truck acceleration/deceleration profiles. Data such as pavement strain measurements and bridge deflections would not be collected by PATH. The IE will explore the possibility of processing the limited PATH FOT data for related ongoing or future USDOT projects on pavements and bridge structures. The IE would work with USDOT to determine the data preparation activities needed.

# 6 Conclusion

This report is an outcome of the Phase 2 IE's support to ITS JPO and its partner agencies (primarily FHWA and FMCSA) on the "Truck Platooning Early Deployment Assessment, Phase 2" project. The report presents a plan to perform additional analysis on truck platoon impact to support an FOT which may take place in the future. The report includes:

- Approach for analyzing the impacts of truck platoon as market penetration changes;
- Analysis Approach for extending the benefits of the truck platoon FOT beyond the geographical boundaries of the FOT route. This involves extrapolating the benefits of truck platoon (as deployed in the FOT) to regional and national levels; and
- Approach to assess the impacts of truck platoon on surrounding vehicle behavior.

The following aspects of truck platoon impacts are recommended for future research:

- The impacts of truck platoons on the structural integrity and maintenance lifecycle of pavement and bridges considering different platoon sizes and gap settings;
- Since the FOT route is within states that are less likely to experience wintery conditions such as icy roads and snow, the performance and safety of truck platoons in wintery conditions should be studied; and
- The FOT involves use of only Volvo trucks with PATH's CACC platooning implementation. In the future, the potential for platooning using trucks from different manufacturing brands should be studied.

# 7 References

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# Appendix: PATH Performance Measures for FOT

Source: PATH Test & Evaluation Plan [forthcoming]

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| OP-001 | Performance measure(s) should capture how long it takes for truck platoon to be formed. | Important | Truck departure delay associated with need to coordinate departures of the platooned trucks. | Difference between actual truck platoon departure time with times when the individual trucks would have been dispatched if they had not been platooned. |
| OP-002 | Performance measure(s) should capture general behavior of trucks/drivers (e.g., speeding behavior, lane changing, etc.) as they seek to form or stay in a platoon. | Most Important | Frequency of lane changing<br>Percentage of manual driving above speed limit (compare platooning trucks to reference trucks) | Number of lane changes made per 1000 miles<br>Percentage of time in manual driving mode that truck speed is at least 5 mph over speed limit for both platooning trucks and the reference truck. |
| OP-003 | Performance measure(s) should capture the usage rate of truck platoon system. | Most Important | Percentage of highway driving time/distance spent in platooning mode | For 3-truck platoon, total time/distance when truck 1 is in manual or ACC and trucks 2 and 3 are in CACC divided by total time/distance.<br>For 2-truck platoon, total time/distance when truck 1 in in manual or ACC and truck 2 is in CACC divided by total time/distance. |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| OP-004 | Performance measure(s) should capture the frequency of splits and re-joins that occur due to unequipped cut-in vehicles | Most Important | Frequency of "cut-in" events and of cut-in events that required disengagements, and durations of each class of cut-in. | # of times a cut-in occurs and # of times a cut-in leads to CACC disengagement per 1000 miles.<br>For all cut-ins, tabulate distribution of duration of cut-in and additional time needed to complete recovery (re-joining). Also sort by 2 vs 3 truck platoon. |
| S-001 | Performance measure(s) should capture how often platoon system notifies (or fails to notify) truck platoon drivers it is no longer controlling longitudinal gap | Important | Frequency of CACC system failures that cause automatic disengagements | # of times the CACC system reports a fault serious enough to require automatic disengagement, and number of these faults that produce alerts to drivers per 1000 miles. |
| S-002 | Performance measure(s) should capture how often platoon drivers disengage platoon system control | Most Important | Frequency of driver-initiated disengagements | # of times a driver manually disengages the system per 1000 miles |
| S-003 | Performance measure(s) should capture the number and types of platoon system failures | Most Important | Frequency of CACC system failures of each primary type (V2V communication, range sensing, vehicle response) | # of times the CACC system reports a fault of each type per 1000 miles. |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| S-004 | Performance measure(s) should capture the overall reliability of the truck platoon system | Most Important | CACC system reliability (fraction of time that the system can be used during a trip when desired) and<br>availability (fraction of vehicle trips that can be dispatched with properly working CACC system) | Reliability: 1 – (total amount of time system has a fault reported divided by total trip time). This is expressed as a percentage.<br>Availability: # of truck trips dispatched with properly working CACC system divided by total # of truck trips dispatched, expressed in percent. |
| S-005 | Performance measure(s) should capture truck driver fatigue (i.e., levels of drowsiness) under platoon and non-platoon modes | Most Important | SmartCap Fatigue Level (1-5) average within 15-minute epochs as well as total durations at each level. | Fatigue level is reported by the SmartCap system (see Section 3.3.3) as a number from 1 to 5, with 1 being hyper-alert and 5 being asleep. Only levels 2-4 are reported, with 4 for some period of time triggering an alert to the driver. |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| S-006 | Performance measure(s) should capture truck platoon driver attentiveness / vigilance(e.g., influence on distraction) | MI Most Important | Number of distraction events flagged within 15-minute epochs, types of distraction events (e.g., device, outside attractions, conversation, etc.) and average length of time that the driver's attention is directed away from forward roadway.<br>(Need to compare drivers of platooning trucks to drivers of reference truck to understand impact of platooning.) | While forward and face video are being recorded, the Jungo AI system (see Section 3.3.3) determines glance direction, head pose, eye closures, etc. The glance direction and head pose elements will provide information on the driver's attention. |
| S-007 | Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between the trucks in the platoon. | Most Important | Frequency of crashes between equipped trucks<br>Frequency of near- crashes between equipped trucks | Total # of crashes between equipped trucks per 1000 miles<br>Total # of near crashes (as defined by a couple of time-to-collision threshold values) between equipped trucks per 1000 miles |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| S-008 | Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and unequipped cut-in vehicles | Most Important | Frequency of crashes between equipped trucks and unequipped cut-in vehicles<br>Frequency of near- crashes between equipped trucks and unequipped cut-in vehicles | Total # of crashes between equipped trucks and unequipped cut-in vehicles per 1000 miles<br>Total # of near crashes (as defined by a couple of time-to-collision threshold values) between equipped trucks and unequipped cut-in vehicles per 1000 miles |
| S-009 | Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and surrounding traffic (excluding cut-in unequipped vehicles) | Most Important | Frequency of crashes between equipped trucks and unequipped, non-cut-in vehicles<br>Frequency of near- crashes between equipped trucks and unequipped non-cut-in vehicles | Total # of crashes between equipped trucks and unequipped non-cut-in vehicles per 1000 miles<br>Total # of near crashes (as defined by a couple of time-to-collision threshold values) between equipped trucks and unequipped non-cut-in vehicles per 1000 miles |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| S-010 | Performance measure(s) should capture the following truck's compliance with the system-defined minimum safe following gap | Most Important | Frequency with which a following truck in CACC mode falls below system-defined min gap<br>Percent of time following truck in CACC mode falls below system-defined min gap | Number of times a following truck in CACC mode falls below system-defined min gap per 1000 miles<br>Duration of time following truck in CACC mode falls below system-defined min gap divided by total time in CACC mode. |
| S-011 | Performance measure(s) should capture instances where platoon system initiates unnecessary collision avoidance (i.e., false positives). | Important | Frequency of inappropriate braking actions by the CACC system (false positives) as reported by drivers. | Specific instances when drivers make a voice or written report of an inappropriate braking action per 1000 miles. (Note this is not collision avoidance, which is not part of CACC functionality) |
| S-012 | Performance measure(s) should capture the accuracy with which the platoon trucks maintain the system's current set/target following gap(s) | Most Important | Root Mean Square Error (RMSE) of distance tracking<br>Max Error of distance tracking | Difference between actual distance to forward truck and desired following distance based on time gap setting. Maximum and RMSE values calculated for each period of continuous CACC usage. |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| M-001 | Performance measure(s) should capture differences in travel time/travel time reliability of truck trips under platooning and non-platooning modes. | Desirable | Difference in Travel Time between platoon trucks and reference truck per trip. | Total travel time of platoon minus total travel time of reference truck from origin to destination. |
| M-002 | Performance measure(s) should capture impacts of truck platoon on tactical behavior of surrounding traffic | Important | The PATH team is not planning to report a specific performance measure for this requirement; however, archived data will be available to enable other analysts to estimate this based on the complete speed profiles of the platooned trucks and reference truck and sensor data on the traffic in the adjacent lanes. | N/A |
| M-003 | Performance measure(s) should capture traffic flow impacts of truck platoons on deployment corridor under different conditions. | Desirable | The PATH team is not planning to report a performance measure for this requirement; however, archived data including complete speed profiles of platooned trucks and reference truck will be available for others to try to use to calibrate traffic simulation models | N/A |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| EE-001 | Performance measure(s) should capture changes in fuel use due to truck platoons | Most Important | Difference in fuel consumption rate between platooning trucks and reference truck | Difference between the average fuel consumption rate of the 2 or 3 platooning trucks and the average fuel consumption rate of the reference truck for each trip (fuel consumption rate will be converted from grams/sec to gallons/hour) |
| EE-002 | Performance measure(s) should capture changes in emission levels due to truck platoons | Desirable | Difference in total emissions per trip between platooning trucks and reference truck | Difference between the total emissions of the 2 or 3 platooning trucks (averaged) and the total emissions of the reference truck for each trip |
| FLT-001 | Performance measure(s) should capture impacts of truck platooning on Fleet Operators daily operations | Desirable | Increased dispatch time due to platooning (per trip)<br>Increased cost due to platooning (per trip) | Difference between dispatch time of platoon trucks and dispatch time of reference truck per trip<br>Difference between logistics cost of platoon trucks and logistics of reference truck per trip |
| FLT-002 | Performance measure(s) should capture cost savings to fleet operators due to fuel efficiency gains | Desirable | Fuel cost savings due to platooning (per 1000 miles) | Difference between average fuel cost of reference truck per 1000 miles and average fuel cost of platooning trucks per 1000 miles |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| FLT-003 | Performance measure(s) should capture impacts of training on truck platoon drivers performance as well as Fleet Operators operations. | Desirable | No quantitative performance measure will be reported. A qualitative assessment will be reported at the end of the test. | Qualitative assessment will be based on results of driver questionnaires. |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| FLT-004 | Performance measure(s) should capture how drivers adapt to the truck platoon system over time. | Important | mean following distance<br>mean time gap<br>rate of engaging in non-driving related activities | Average following distance per trip by driver: Integrated Distance-Gap over distance divided by the trip distance<br>Average time gap per trip by driver: Integrated Time-Gap over distance divided by the trip distance |
| FLT-005 | Performance measure(s) should capture driver acceptance/satisfaction of/with truck platoon technology | Most Important | Subjective rating scale scores (i.e. 0 to 10) | A subjective rating of driver acceptance/satisfaction assigned by the drivers during interviews. |
| FLT-006 | Performance measure(s) should capture Fleet Operators' acceptance/satisfaction of/with truck platoon technology. | Most Important | Subjective rating scale scores (i.e. 0 to 10) | A subjective rating of Fleet Operator acceptance/satisfaction assigned by the fleet operator managers during interviews. |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| FLT-007 | Performance measure(s) should capture how truck platoons affects driver behavior (e.g., highway following gap) in non-platoon situations. | Most Important | mean following distance<br>mean time gap | Average following distance by driver<br>Average time gap by driver |
| II-001 | Performance measures should capture the impact of truck platoon on bridge structures. | MI Most Important | The PATH team is not planning to report a specific performance measure for this requirement; however, truck characteristics and speed profiles can be provided for USDOT analysis | N/A |
| II-002 | Performance measure(s) should capture information on infrastructure configuration/characteristics suitable for truck platoons and vice versa, as experienced during trip. | Important | Percentage of highway driving time/distance spent in platooning mode<br>(for specific challenging scenarios within the ODD) | total time/distance when following truck(s) are in CACC mode divided by total time/distance for situations such as:<br>• Positive or negative grades above defined threshold values<br>• Curve radii below defined threshold values<br>• Ambient traffic speeds below defined threshold values<br>• Traffic density above defined threshold values |
| II-003 | Performance measure(s) should capture impacts of truck platoon on roadway pavements. | Desirable | The PATH team does not plan on having a performance measure for this requirement since it is impractical. | N/A |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| SL-001 | Performance measure(s) should capture interactions between truck platoon drivers and law enforcement officials | Most Important | Counts of instances of law enforcement pull-overs<br>Rates of instances of law enforcement pull-overs | Number of times a test truck (control or platoon) is pulled over by law enforcement for inspection or other reason<br>Number of times a test truck (control or platoon) is pulled over by law enforcement per 1000 miles driven |
| SL-003 | Performance measure(s) should capture impacts/differences (if any) in truck inspection and enforcements for truck platooning | Desirable | Measures listed above for SL-001 plus: Delay time due to being pulled over by law enforcement | Measures listed above for SL-001 plus: Total amount of time each truck is delayed by pull overs, separately tabulated for platooned trucks and reference truck, and normalized by hours of driving in each mode. |

| ID | Requirement | Priority | Performance Measures | Definition |
|---|---|---|---|---|
| VED -001 | Performance measure(s) should provide information regarding drivers opinions on truck platoon equipment design deficiencies observed | Important | No quantitative performance measure will be reported. A qualitative assessment will be reported at the end of the test. | Qualitative assessment will be based on results of driver questionnaires. |
| VED -002 | Performance measure(s) should capture the reliability of V2V communications between trucks in a platoon. | MI Most Important | Rate of DSRC failures<br>Count of handshake failures | Number of DSRC communications failures between each pair of trucks per 1000 miles driven.<br>Note: DSRC failure is a drop out of more than 2 secs.<br>Number of times when DSRC failed to connect at start of platoon trip |
| VED -003 | Performance measure(s) should capture the effectiveness of information provided to drivers of following trucks | Important | No quantitative performance measure will be reported. A qualitative assessment will be reported at the end of the test. | Qualitative assessment will be based on results of driver questionnaires. |

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free “Help Line” 866-367-7487
www.its.dot.gov

FHWA-JPO-22-962

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