

Truck Platooning Early Deployment Assessment– Independent Evaluation

Performance Measures for Evaluating Truck Platooning Field Deployments

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16. Abstract <p>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 is to develop a concept and proposal for deploying and assessing a commercial truck platoon system. Field test deployment and assessment will occur in Phase 2.</p> <p>As part of Phase 1, the Independent Evaluator (IE) developed requirements for performance measures based on which each of the three Phase 1 teams developed performance measures to evaluate their Phase 2 field test deployments. The purpose of this report is to summarize the key performance measures proposed for Phase 2 field operational test as well as performance measures from other truck platooning efforts around the world. This will guide transportation agencies on selecting appropriate performance measures for evaluating future truck platooning deployments. The report also includes:</p> <ul style="list-style-type: none"> • Discussions of experimental designs for truck platooning field deployments; and • Contextual applications of performance measures for evaluating truck platooning field deployments. 			
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Truck Platooning Early Deployment Assessment– Independent Evaluation: Performance Measures for

Evaluating Truck Platooning Field Deployments

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Executive Summary

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 promise 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 (FHWA, EAR Program). In the future, the commercial trucking industry is anticipating the deployment of truck platooning systems based on vehicle-to-vehicle (V2V) communications. System-wide impacts and the impact on truck drivers, fleet owners, and light duty vehicle drivers still needs 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) 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. 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 vehicle platooning field operational test that has an observable and measurable near-term impact. The field test deployment and assessment will occur during Phase 2 of the project. This project is expected to help answer research questions related to human factors impacts on truck drivers, interactions between truck platoons and surrounding traffic, fleet operator impacts, fuel efficiency, policy, and other potential impacts. Three teams were selected by FHWA to participate in the 9-month Phase 1 project (hereafter referred to as Phase 1 Awardees). The Awardee teams are led by Battelle, California PATH, and CDM Smith. Only Phase 1 Awardees (i.e., Battelle, CDM Smith, and California PATH) were eligible to submit Phase 2 proposals.

An Independent Evaluator (Noblis) was selected by ITS JPO to provide technical support to Phase 1 Awardees on how to plan and evaluate their proposed truck platoon field deployments. Among the responsibilities of the Phase 1 Independent Evaluator (IE) is the need to define requirements for performance measures for eight key areas of interest that will be used by both the IE, and Phase 2 teams, to evaluate the performance of truck platooning systems tested as part of an early deployment in Phase 2. In their Test and Evaluation Plans, the Phase 1 Awardees proposed a host of performance measures across the eight key areas to be used in assessing their proposed Phase 2 field deployments.

Research Approach

Although the Phase 1 Awardees identified many performance measures for evaluating their proposed Phase 2 truck platooning field deployments, those measures were based on their specific Phase 2 deployment approach and considered realistic limits to the project's length, potential funding level, and implementation feasibility. As a result, their proposed performance measures may not be considered exhaustive for all truck platooning field deployment evaluations.

In order to produce a more expansive list of performance measures for evaluating truck platooning field deployments, a two-step approach was employed. Firstly, Test and Evaluation Plan reports submitted by the Phase 1 Awardees were reviewed to identify performance measures being proposed for evaluating the truck platooning field deployments in Phase 2. Secondly, literature from other past and ongoing truck platooning projects both in the U.S. (e.g., commercial truck platooning demonstration in Texas – Level 2 automation) and outside of the U.S. (e.g., The European Union's ENSEMBLE project) were scrutinized for additional performance measures information. Findings from both reviews were synthesized to produce the key truck platooning deployment performance measures and associated information presented in this report.

Key Performance Measures

For each key performance measure identified, the following were discussed:

- **Definition** – Description of the performance measure.
- **Interpretation & Use(s)** – Interpretation of the performance measure within the context of truck platooning and how to use it in assessing the impacts of truck platooning technology.
- **Data Needs** – Describes data needs of the performance measure and how to use the data to calculate the performance measure.
- **Evaluation Approach** – Discusses the different evaluation methodologies under which the performance measure can be used to assess the impacts of truck platooning technology.
- **Challenges** – Discusses the challenges (e.g., technical, operational, financial, etc.) associated with measuring the performance measure.

Based on their characteristics and usage, each key performance measure was associated with one of the eight performance measure requirements categories developed by the Phase 1 IE. The requirements were categorized into eight groups based on the eight key areas of interest identified by FHWA in the BAA. The key areas and their abbreviations (as used in the rest of this report) are as shown below:

1. Platoon Operational Characteristics (OP) – This includes the formation, operation, reconfiguration, and termination of a platoon.
2. Safety (S) – This includes aspects of driver and vehicle performance that impact safety, as well as interactions with surrounding traffic.
3. Mobility (M) – This includes impacts on congestion and traffic flow, including constraints imposed by temporary or permanent roadway environment characteristics (e.g., work zones, merge areas, incidents, weather conditions, etc.).
4. Energy and Emissions (EE) – This includes potential for fuel savings and accompanying reductions in emissions and release of pollutants
5. Fleet Operator and Driver Impacts (FLT) – This includes impacts on driver training, driver performance, fatigue, workload, and attention, operational costs
6. Infrastructure Impacts (II)– This includes identification of infrastructure characteristics and requirements that would support safe and extended performance of truck platoons
7. State and Local Government Impacts (SL) – This includes impacts to maintenance and operations costs, inspection programs, enforcement procedures, driver licensing, policies associated with platooning operations, etc.
8. Vehicle Equipment Design Implications (VED) – This includes vehicle and vehicle equipment needs introduced by the use of truck platooning systems.

Discussion on Other Considerations

The key performance measures identified and discussed in this report are useful for conducting impacts assessment for truck platooning field deployments with similar goals and objectives as this project. However, to use these performance measures correctly, it must be within the appropriate context. For example, the performance measures are not intended to evaluate the version or maturity level of the specific truck platooning technology used in the deployment test as compared to some other version of truck platooning technology. In addition, some key considerations regarding field deployment evaluations must be taken into account. The report briefly discusses these contextual applications and key considerations.

Conclusions

This report is an outcome of the Phase 1 IE's support to ITS JPO and its partner agencies (primarily FHWA and FMCSA) on the "Truck Platooning Early Deployment Assessment, Phase 1" project. The report includes:

- Synthesis of performance measures for evaluating truck platooning field deployments obtained from Phase 1 Awardees as well as from other truck platooning projects around the world;
- Discussion of experimental designs for truck platooning field deployments; and
- Contextual applications of the performance measures developed in this report.

While many performance measures have been presented in this report, the actual performance measures that will be used to evaluate the impacts of truck platooning technology in Phase 2 will be dependent on the Awardee's proposed evaluation plan as well as the availability and quality of field data collected during the deployment period.

1 Introduction

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 promise 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 is anticipating the deployment of truck platooning systems based on vehicle-to-vehicle (V2V) communications. System-wide impacts, the impact on truck drivers, fleet owners, and light duty vehicle drivers still needs 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) 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. 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 vehicle platooning field operational test that has an observable and measurable near-term impact. The field test deployment and assessment will occur during Phase 2 of the project. Specific research questions to be answered include:

- What are the human factors impacts on truck drivers in long-haul operation of a truck platoon?
- How are 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 (fuel savings, safety, operating costs, vehicle maintenance, mobility/travel time) as well as the risks (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?

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.

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 1 of this project. The role of the IE in Phase 1 was to:

- Define requirements for performance measures that will be used by both the independent evaluator, and Phase 2 teams, to evaluate the performance and impacts of truck platooning systems tested as part of an early deployment. Note that the IE did not develop performance measures; rather, Phase 1 Awardees used the requirements defined by the IE to develop performance measures for their proposed truck platoon deployments.

- Plan and conduct outreach and coordination events with Phase 1 Awardee teams to provide guidance and offer an opportunity for feedback and questions around performance measure and evaluation methodology development.
- Support Phase 1 Awardee teams to identify performance measures and data requirements; procedures to collect, store, manage, and provide access to data; and evaluation plans.

1.1 Truck Platooning Concept

Truck platooning uses technology, including V2V wireless communication, to allow trucks to follow each other safely and more closely than conventional driving. For example, using V2V communications, two trucks in a platoon can “electronically couple” such that the following truck automatically responds based on sensors and communications between the two trucks. Truck platooning technology can be classified as a cooperative automated vehicle (AV) system because it uses both on-board systems plus communications between trucks to provide information critical to driving. The role of the truck driver in a following truck is dependent on the level of automation incorporated into the truck platooning technology. According to the Society of Automotive Engineers (SAE) J3016 standard, there are 6 levels of driving automation (numbered 0 through 5) (3). For this project, Awardees are required to propose and deploy cooperative automated truck platooning system with minimum SAE Level 1 automation capabilities. The first three SAE levels of driving automation are briefly described below.

- Level 0 (No driving Automation) – The human driver is fully in charge of the entire driving task.
- Level 1 (Driver Assistance) – The human driver is in charge of either the longitudinal vehicle motion control or lateral vehicle motion control. At this level, both longitudinal and lateral vehicle controls cannot be automated at the same time. In the context of truck platooning, the Level 1 automated control of interest is longitudinal control. It is also expected that the human driver performs the remainder of the driving task (e.g., observing roadway driving conditions, detection of roadway hazards, etc.).
- Level 2 (Partial Driving Automation) – The automation system is in charge of both longitudinal and lateral vehicle control. This allows for both hands-off (from steering wheel) and feet-off (from accelerator and brake) driving. However, the human driver is expected to perform the remainder of the driving task (e.g., observing roadway driving conditions, detection of roadway hazards, etc.).

1.2 Truck Platooning Field Deployment Evaluation

A Field Operational Test (FOT) like the truck platooning early deployment assessment is a method used to assess or verify that newly developed transportation technologies can deliver real-world benefits (4). Due to the relatively significant amount of resources (e.g., time, funding, institutional arrangements, etc.) required to conduct FOTs, most new transportation technologies are first evaluated using modeling and simulations to estimate potential benefits and impacts. In addition to modeling and simulation, and still prior to an FOT, there is usually prototype testing in controlled environments or limited areas to assess technical functionalities and potential benefits. Subsequently, FOTs are used to verify whether estimated benefits obtained from models/simulations and controlled prototype tests can be realized in uncontrolled real-world conditions.

For the truck platooning deployment evaluation to be effective and informative, it must be carefully planned and executed, so that the true impacts on the transportation system can be isolated and quantified. This implies that, an appropriate evaluation design (see Section 3.3) must be identified and incorporated into the FOT implementation plan, to ensure that relevant data needed for evaluation are collected (4). Regardless of which evaluation design is employed, it must be possible to compare performance of the transportation system when truck platooning is in use with a baseline condition during which the truck platooning technology is not in use.

An essential component of evaluating the truck platooning early deployment is the need for performance measures. They provide a means to capture the true impacts of the technology on the transportation system/ transportation users by comparing them across deployment and baseline periods. Choosing the right and appropriate performance measures is very critical. This is because, failure to identify appropriate performance measures may lead to false conclusions. For this reason, the choice of performance measures should be directly tied to the goals and performance measure requirements established for the truck platooning deployment.

1.3 Purpose of the Report

The purpose of this report is to summarize key performance measures for evaluating truck platooning field deployments. The report presents detailed information (e.g., data needs, evaluation approach, uses, etc.) about each performance measure to guide transportation agencies on selecting appropriate performance measures for evaluating future truck platooning field deployments. It also touches on experimental designs as well as key considerations regarding use of performance measures in evaluating truck platooning field deployments.

1.4 Research Approach

A two-step approach was used to develop this report. Firstly, Test and Evaluation Plan reports submitted by the three Phase 1 Awardees were reviewed to identify performance measures being proposed for evaluating the truck platooning field deployments in Phase 2. Secondly, literature from other past and ongoing truck platooning projects both in the U.S. (e.g., commercial truck platooning demonstration in Texas – Level 2 automation) and outside of the U.S. (e.g., The European Union's ENSEMBLE project) were scrutinized for additional performance measures information. Findings from both reviews were synthesized to produce the key truck platooning deployment performance measures and associated information presented in this report.

1.5 Organization of the Report

This report is organized as follows:

- The first Chapter provides background information about the Truck Platooning Early Deployment Assessment project, high-level description of truck platooning field deployment evaluation, and purpose of the report;
- Chapter 2 discusses key performance measures for evaluating truck platooning field deployments;

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- Chapter 3 discusses other considerations regarding the use of performance measures presented in this report; and
- Chapter 4 presents conclusions for this report.

2 Key Performance Measures

As part of its role, the Phase 1 IE developed a set of requirements to guide the development of performance measures and evaluation plans by Phase 1 Awardees for evaluation of Phase 2 field test(s) (5). The requirements were categorized into groups based on the eight key areas of interest identified by FHWA in the BAA. The eight key areas and their abbreviations (as used in the rest of this report) are as shown below:

1. Platoon Operational Characteristics (OP) – This includes the formation, operation, reconfiguration, and termination of a platoon.
2. Safety (S) – This includes aspects of driver and vehicle performance that impact safety, as well as interactions with surrounding traffic.
3. Mobility (M) – This includes impacts on congestion and traffic flow, including constraints imposed by temporary or permanent roadway environment characteristics (e.g., work zones, merge areas, incidents, weather conditions, etc.).
4. Energy and Emissions (EE) – This includes potential for fuel savings and accompanying reductions in emissions and release of pollutants
5. Fleet Operator and Driver Impacts (FLT) – This includes impacts on driver training, driver performance, fatigue, workload, and attention, operational costs
6. Infrastructure Impacts (II)– This includes identification of infrastructure characteristics and requirements that would support safe and extended performance of truck platoons
7. State and Local Government Impacts (SL) – This includes impacts to maintenance and operations costs, inspection programs, enforcement procedures, driver licensing, policies associated with platooning operations, etc.
8. Vehicle Equipment Design Implications (VED) – This includes vehicle and vehicle equipment needs introduced by the use of truck platooning systems.

The remainder of this Chapter focuses on identifying key performance measures that correspond to the respective requirements for the eight key areas. For performance measures that did not fit nicely into any of the requirements, they were discussed under the general key area they fall under (see section 2.1.1). The requirements have unique identifiers (ID) that are prefixed by the key area they belong to, followed by the requirement number for that key area. For example, OP-001 is interpreted as requirement number one in the Platoon Operational Characteristics key area. Note that performance measures with an asterisk sign were identified from sources outside of the Phase 1 Awardees Test and Evaluation Plans. For each key performance measure identified, the following were discussed:

- **Definition** – Description of the performance measure.
- **Interpretation & Use(s)** – Interpretation of the performance measure within the context of truck platooning and how to use it in assessing the impacts of truck platooning technology.
- **Data Needs** – Describes data needs of the performance measure and how to use the data to calculate the performance measure.
- **Evaluation Approach** – Discusses the different evaluation methodologies under which the performance measure can be used to assess the impacts of truck platooning technology.

- **Challenges** – Discusses the challenges (e.g., technical, operational, financial, etc.) associated with measuring the performance measure.

2.1 Platoon Operational Characteristics

Truck platoon formation can occur through ad hoc means (i.e., truck drivers on the road decide to platoon without prior planning/arrangement), local coordination (i.e., coordinated by fleet dispatch operations center or third party service while trucks are on the road), and scheduled coordination (i.e., platoon formation pre-planned before trucks get on the road). Once platoons are formed, trucks will remain in platoon mode until the platoon is dissolved as a result of many factors (e.g., cut-ins by unequipped vehicles, platoon splits, truck driver disengagement due to external conditions, etc.). Because cut-ins are inevitable, the platoon system needs to be designed to automatically handle a cut-in. Performance measures for this key area should be able to capture the dynamics of truck platoon operations. The requirements for performance measures developed for this key area and the corresponding performance measures are presented below.

OP-001: Performance measure(s) should capture how long it takes for truck platoon to be formed based on the choice of coordination strategy being used and other factors.

Platoon Formation Time

Definition – This is defined as the time duration between platoon mode activation (i.e., when platooning system is turned on and ready to engage) and platoon engagement (i.e., when actual platooning begins), measured in seconds.

Interpretation & Use(s) – This performance measure captures the ability of truck platoons to be formed efficiently under different conditions (e.g., traffic, weather, etc.) and formation strategies. Platoon formations that take longer than normal (from a driver’s standpoint) may limit the number of times they would attempt to form a platoon. Platoon formation may be coordinated in which case trucks leave the journey starting point (e.g., a depot or logistics center) in a pre-arranged order and initiate platoon formation under the right conditions (most likely when they get on the highway). Platoon formation under this strategy may encounter less interference and ultimately less formation time. Conversely, ad hoc platoon formation (i.e., trucks within proximity form a platoon on the fly) on the highway or reformation of a dissolved platoon may encounter more interference and would possibly require more time. This performance measure enables both fleet operators and transportation system managers to understand likely driver acceptance of the truck platooning technology and how it may potentially impact highway traffic, respectively.

Data Needs – The key data elements needed to estimate platoon formation time include platoon records such as time of platoon activation and time of platoon engagement; type of platoon formation strategy (i.e., coordinated or ad hoc/reformation); GPS traces of platoon trucks; and external data such as weather and traffic conditions.

Evaluation Approach – Platoon formation time can be analyzed across different platoon formation strategies to understand how the formation strategies affect platoon formation time. Also, platoon formation time may be influenced by individual driver behavior. Therefore, the analysis could investigate how driver behavior affects platoon formation time by first analyzing within driver and then summarizing across drivers.

Challenge(s) – The main challenge in measuring this performance measure is the technical ability to accurately record the two time points (i.e., time of platoon activation and time of platoon engagement), formation strategy type, and the conditions under which platoon formation occurs.

OP-002: Performance measure(s) should capture general behavior of trucks/drivers (e.g., speeding behavior, lane changing behavior, etc.) as they seek to form a platoon.

Number of Lane Changes

Definition – This is the number of lane change maneuvers of trucks during platoon formation, expressed as a ratio (e.g., per 1,000 miles, per 100 platoon formation attempts, etc.).

Interpretation & Uses – This measure characterizes platoon truck drivers' behavior as they seek to form a platoon (e.g., do trucks make risky lane changes to form a platoon?). Lane change maneuvers have both safety (often used as a surrogate safety measure) and mobility impacts on traffic. To ensure safe and stable traffic conditions, lane change maneuvers must be kept to a minimum. Therefore, a relatively higher number of risky lane change maneuvers by truck drivers seeking to form a platoon is undesirable. This performance measure provides useful information to fleet operators and transportation system managers respectively about the safety of platoon drivers and traffic impacts. An important aspect of this performance measure is the analysis time horizon. Although platoon formation time is calculated from the time platoon trucks activate (i.e., turn on platoon mode) to time of engagement (i.e., when platooning actually begins), the process of forming a platoon may be initiated prior to activating the platoon mode of trucks. For example, a platoon truck driver lagging significantly behind a leading truck may execute some lane change maneuvers and draw closer to the leading truck before turning its platooning mode on. Therefore, it is important to choose an appropriate analysis time horizon (e.g., 2 minutes prior to platoon mode activation to time of platoon engagement) to ensure that the true behavior of platoon truck drivers during platoon formation is captured.

Data Needs – The key data elements needed include time-stamped lane changing maneuver logs, GPS traces of platoon trucks, and external conditions data such as weather, traffic regimes, etc.

Evaluation Approach — To assess the driving behavior of drivers as they seek to form platoons using the number of lane change maneuvers, multiple evaluation approaches can be used. At a minimum, the rate of lane changes of platoon truck drivers on a roadway/travel route before the field deployment (i.e., baseline period) can be compared with corresponding rates during the deployment period for the same drivers (i.e. non-randomized simple before/after analysis) and same roadway/travel routes. Similarly, the rate of lane changes during a deployment period can be compared for the same driver between when the truck is being driven in manual mode and when the driver attempts to join a platoon (i.e., non-randomized with and without analysis). A more superior and rigorous evaluation approach is to compare the rate of lane changes among treatment trucks (i.e., trucks seeking to form a platoon) and control trucks (trucks within proximity of treatment trucks and being driven in manual mode) traveling in the same traffic conditions during the deployment period (i.e., quasi or randomized experimental design) to account for confounding factors.

Challenges – One of the key challenges is to have the ability to log the needed data (e.g., time-stamped lane change maneuvers executed by trucks) before and during field deployment. Another challenge is the possibility of having treatment (i.e., platoon trucks) and control trucks traveling in proximity if a quasi or randomized experimental design is used. For field deployments that involve fleet operator partners, their schedules would have to be modified to ensure both platoon and control trucks begin their journeys at the same time. Such schedule modifications may present an operational challenge. Finally, the cost of having a control truck participating in a field deployment in addition to platoon trucks will be relatively higher.

Speed Variability/ Average Speed

Definition – Speed variability is the standard deviation of truck speeds during platoon formation. The mean of the speed distribution of platoon trucks during platoon formation is the average speed.

Interpretation & Use(s) – Speed variability captures the driving behavior of truck drivers in terms of speed distribution during the platoon formation period. Like lane changes, speed variability has both safety and mobility impacts and the magnitude of the variability provides an insight into the safety risk and potential disruptions to traffic flow during platoon formation. A higher speed variability during platoon formation suggests truck platoon drivers driving at a wide range of speeds (i.e., accelerating and decelerating successively at shorter time intervals), thereby increasing safety risks and negatively impacting traffic flow. A closely related measure is the average speed of platoon trucks during platoon formation. The average speed is a general indicator of how fast or slow the platoon trucks are driving during platoon formation. These two performance measures provide insights into the speed behavior of platoon trucks during platoon formation. Just as in “number of lane changes” measure, the analysis time horizon is very critical to capturing the right information. It should include the immediate time preceding platoon activation mode.

Data Needs – Data elements needed for estimating this measure include time-stamped platoon truck speeds, type of platoon formation strategy (i.e., coordinated or ad hoc/reformation) and external conditions data such as weather, traffic regimes, lighting conditions, etc.

Evaluation Approach – Speed variability during platoon formation for platoon trucks on a roadway/travel route can be compared with corresponding baseline speed variability (i.e., prior to field deployment or non-platooning episodes of deployment period) to understand truck platoon driver behavior leading up to the formation of platoons. To account for confounding factors, comparison should be made between similar time periods (day vs night), weather (dry vs rain) and other external conditions such as traffic regime. Also, the average speed of platoon trucks during platoon formation can be compared with posted speed limits to determine if there is over speeding. A more superior and rigorous evaluation approach is to compare speed variability/average speed between platoon and control trucks traveling in the same traffic conditions during the deployment period (i.e., quasi or randomized experimental design) to account for confounding factors. In addition, the analysis can be summarized based on the type of platoon formation strategy (e.g., coordinated or ad hoc/reformation) and external conditions such as weather, traffic conditions, lighting conditions, etc.

Challenges – One key challenge is the technical ability to collect the needed data (e.g., time-stamped truck speed) before and during field deployment. Another challenge is the relatively higher cost of having platoon trucks and control trucks participating in the field deployment. For field deployments that involve fleet operator partners, their schedules would have to be modified to ensure both platoon and control trucks begin their journeys at the same time.

OP- 003: Performance measure(s) should capture the usage rate of truck platoon system categorized with respect to different conditions/factors encountered during trips.

Percent of Highway Driving Time/Distance Spent in Platooning Mode

Definition – Ratio of time spent, or distance travelled while in platoon mode compared with total trip hours or trip distance.

Interpretation & Uses(s) – This performance measure reflects the usage rate of truck platoon technology during truck trips. It provides insights into whether there is a business case for this technology. All the benefits of truck platooning technology (e.g., reduction in fuel use, reduction in

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Truck Platooning Early Deployment Assessment– Independent Evaluation: Performance Measures for

crashes, etc.) can be realized in significant magnitudes only if the technology is used. If the share of miles (or trip time) suitable for platooning is high, the accrued benefits of truck platooning technology would be high and vice versa. Hence, this performance measure helps decision makers such as fleet operators to decide whether to invest in truck platooning technology. This performance measure can be categorized based on varying conditions such as weather, traffic regimes, work zones, and other applicable conditions expressed in the Operational Design Domain (ODD) of the truck platoon system (e.g., gap settings) and the planned operational environment. If the truck platoon technology enables platooning on both highways and surface streets, then the rate of usage should include all miles/time traveled/spent platooning on both facility types.

Data Needs – Data elements needed to estimate this performance measure includes log of truck driving mode (i.e., manual mode vs platoon mode), truck trip miles/time, and external conditions such as weather, traffic regimes, roadway grade, etc.

Evaluation Approaches – This performance measure does not require any experimental design because no baseline comparison is needed.

Challenges – The main challenge in estimating this performance measure is to have the technical ability to log/collect the needed data (e.g., truck driving mode, weather data, traffic regime data) during field deployment.

OP- 004: Performance measure(s) should capture the frequency of splits and re-joins that occur due to unequipped cut-in vehicles (considering actual gap between trucks) or middle platoon truck exits (if 3-truck platoon), categorized with respect to different conditions/environments encountered during trip.

Rate of Splits/Rejoins Due to Cut-Ins/Exits

Definition – This is the number of splits/rejoins due to cut-ins by unequipped vehicles, expressed as a ratio.

Interpretation & Use(s) – This performance measure seeks to determine how frequently platooning is interrupted in the course of a trip as a result of cut-ins by unequipped vehicles or departure of a middle truck in a three-truck platoon scenario. When a cut-in/ exit occurs, a platoon would typically dissolve/split (ending platooning) and rejoin (restarting platooning) after the unequipped vehicle or middle truck departs. This performance measure helps to understand how the truck platoon system handles splits due to cut-ins or exits. A higher frequency of splits and rejoins (e.g., multiple splits/rejoins per mile) has the potential to become a nuisance to truck platoon drivers. It may also dissuade fleet operators from adopting truck platoon technology because it may negate potential fuel savings. Understanding the conditions that influence frequency of splits and re-joins (e.g., gap settings, traffic regimes, geographical factors (e.g., urban vs rural corridors), weather conditions, lighting conditions, etc.) may help to determine when and where platooning is more suitable. A closely related performance measure, rate of cut-ins (e.g., number of cut-ins per 1,000 miles) can be indirectly estimated from this performance measure by counting the number of truck platoon splits/rejoins due to cut-ins and expressing it as a ratio.

Data Needs – Key data elements required include log of time-stamped truck platoon splits/rejoins due to cut-ins/ exits, GPS traces of platoon trucks, truck trip miles, external conditions data (e.g., weather, traffic regime, etc.) and platoon driving data such as platoon gap settings.

Evaluation Approach – The analysis involves summarizing the rate of splits/rejoins based on factors such as gap settings, traffic regimes, lighting conditions, geographical locations, and others.

Challenges – The main challenge in estimating this performance measure is the technical ability to log/collect the needed data (e.g., time-stamped truck platoon splits/rejoins, weather data, traffic regime data, gap settings, etc.) during field deployment.

Other Operational Characteristics Performance Measures

A couple of identified performance measures that fall under truck platoon operational characteristics did not fit nicely into any of the four performance measure requirements defined by the IE in Phase 1. These performance measures are discussed below.

Rate of Interrupted Platoon Formation Attempts* (6)

Definition – Number of failed platoon formation attempts, expressed as a rate (e.g., per 1,000 miles, per 100 attempts).

Interpretation & Use(s) –As trucks seek to form a platoon (i.e., either ad hoc or reformation), there are a host of instances in which such attempts may be unsuccessful. For example, two equipped nearby trucks whose platooning systems have been activated (i.e., turned on) and are ready to couple may have to abort platoon formation due to a cut-in by an unequipped vehicle that requires the following truck to reduce its speed. Similarly, the attempt of two neighboring equipped trucks to form a platoon may be unsuccessful due to communication failure between the lead and following truck. This performance measure is intended to capture such failed attempts, taking into account the contributing factors. Since drivers may be frustrated by frequent instances of failed platoon formation attempts, the information to be provided by this performance measure will enable fleet operators to understand likely driver acceptance of the technology.

Data Needs – The key data elements needed to estimate the rate of interrupted platoon formation attempts include platoon driving data such as platooning system activation status data (on/off), GPS traces of platoon trucks, platoon system diagnostic data, truck platoon driver log/notes, and external data such as weather and traffic conditions.

Evaluation Approach – Analyze collected data and summarize rate of interrupted platoon formation attempts according to factors such as cut-ins, communication failure, roadway characteristics, etc. To account for the influence of individual driver behavior, the analysis can be conducted within driver before summarizing across drivers.

Challenge(s) – The main challenge in measuring this performance measure is the technical ability to collect needed platooning and external conditions data.

Speed Variation of Steady-State Platooning* (7)

Definition – Standard deviation of platooning truck speeds while in steady-state cruising mode.

Interpretation & Use(s) –Truck platoon operations involve three key stages. These include the formation stage, steady-state stage, and the dissolution stage. The formation and dissolution stages respectively deal with trucks coupling together through coordinated or ad hoc means (as explained in “platoon formation time” performance measure) and platooning operations being disengaged so that each truck drives individually. At steady-state, following truck drivers are tasked with actively steering their trucks (not required in SAE Level 2) and monitoring truck vehicle status and surrounding traffic conditions. The speed of the following truck is controlled by the platoon system based on factors such as target gap between lead and following truck, speed of the lead truck, etc. This performance measure seeks to capture the variation in speed as platoon trucks travel in steady-state cruising mode. This information is important because it indirectly captures the acceleration/deceleration profile

of platoon trucks which ultimately affects fuel consumption rates. Since most truck platooning benefits accrue during steady-state driving (8), it is important that speed variability in this stage is minimal.

Data Needs – The key data elements needed to estimate this measure include platoon driving data such as truck driving mode (i.e., manual or platooning), platoon truck speeds, platoon truck acceleration data, GPS traces of platoon trucks, and external conditions data such as weather, traffic regimes (e.g., different levels of congestion), roadway grade, and others.

Evaluation Approach – Calculate speed variability of platoon trucks during steady-state driving and summarize according to external factors such as traffic regime, roadway grade, weather conditions, lighting conditions (e.g., day vs night), and others.

Challenge(s) – The key challenge in measuring this performance measure is the technical ability to collect needed platooning and external conditions data.

2.2 Safety

Despite the potential benefits of truck platooning, there are still concerns regarding safety implications of implementing commercial truck platooning. Those concerns include platoon trucks not able to swiftly adapt to changing traffic conditions due to vehicle mechanics (e.g., brake performance of following truck), reduced visibility of following truck drivers (i.e., driver performance), highway hypnosis (i.e., truck drivers becoming over reliant on truck platoon system), and impact of truck platoons on safe behavior of other drivers (e.g. cut-ins or speeding to overtake platoons) (9) (10). Therefore, safety performance measures should be able to capture aspects of truck driver and truck performance that impact safety, as well as interactions with surrounding traffic. The requirements and corresponding key performance measures for assessing the safety of truck platooning field deployment are discussed below.

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 and/or lateral movement and the reason(s) for such notifications.

Rate of Longitudinal/Lateral Control Dropout Notifications

Definition – Frequency of instances where drivers receive/fail to receive alerts/notifications when truck platooning system automatically disengages from longitudinal/lateral control, expressed as a ratio.

Interpretation & Use(s) – This performance measure captures the frequency of instances where truck platoon drivers receive (or fail to receive) notifications (which may be of varied types) from the truck platoon system that it is no longer controlling longitudinal and/or lateral movements (applies to Level 2 only) of following trucks. Disengagements under this performance measure include disengagements due to technical system failure or the platoon trucks moving outside of their ODD. The importance of this performance measure is that it provides useful information about how often a driver must assume longitudinal/lateral control of the following truck (e.g., 50 notifications/alerts per 1,000 miles). High rates of disengagement notifications may negatively influence platoon drivers' behavior in terms of the desire to platoon and the possibility of completely turning the system off. A more critical scenario may arise in instances where the truck platoon system fails to notify following truck drivers that it is no longer in charge of longitudinal/lateral control. Rates of occurrence of such failures must be kept to zero.

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Data Needs – Data elements required include platoon system data (e.g., number of disengagements, number of notifications/alerts, number of disengagements without notifications/alerts, truck trip miles), roadway data (e.g., grades, curvature, etc.), GPS traces of platoon trucks, and other external conditions such as weather, traffic regimes, etc.

Evaluation Approaches – The analysis involves summarizing the rate of longitudinal/lateral control dropout notifications based on factors such as traffic regimes, lighting conditions, geographical locations, and others. Similarly, summary analysis of disengagements that did not produce driver alerts/notifications can also be performed based on above-mentioned factors.

Challenges – The main challenge in estimating this performance measure is the technical ability to log/collect the needed truck platoon system data (e.g., number of disengagements, number of notifications/alerts, truck trip miles, etc.) and external conditions data (e.g., weather, roadway) during field deployment.

S-002: Performance measure(s) should capture how often platoon drivers disengage platoon system control and the reason(s) for such disengagements.

Rate of Driver-Initiated Platoon Disengagements

Definition – Frequency of times a driver manually disengages the platooning system, expressed as a ratio (e.g., per 1,000 miles driven).

Interpretation & Use(s) – This performance measure captures the frequency of instances where truck platoon drivers exercise professional judgement by disengaging the truck platooning system's longitudinal/lateral control. These driver-initiated disengagements could arise as a result of the presence of conditions outside of the ODD. These include congested traffic conditions, inclement weather, construction area, prior to a break or exit from the roadway, entering an interchange area, etc. However, driver-initiated disengagements that arise due to technical failures are more critical. High prevalence of such disengagements may lead to driver disaffection regarding the usage of the platooning system. The rate of driver-initiated disengagements may be classified according to these varying conditions to better understand where platooning is suitable.

Data Needs – Data elements required include platoon system data (e.g., number of disengagements, truck trip miles), roadway data (e.g., grades, curvature, etc.), GPS traces of platoon trucks, and other external conditions such as weather, traffic regimes, etc.

Evaluation Approach – The analysis involves summarizing the rate of driver-initiated platoon disengagements based on factors such as traffic regimes, lighting conditions, geographical locations, and others.

Challenges – The main challenge in estimating this performance measure is the technical ability to log/collect the needed truck platoon system data (e.g., number of disengagements, truck trip miles, GPS traces, etc.) and external conditions data (e.g., weather, roadway, traffic regimes, etc.) during field deployment.

S-003: Performance measure(s) should capture the number and types of platoon system failures (e.g., failure in coordinated braking between leading and following truck, V2V communication signal loss, malfunctioning radar/lidar, RF interference, etc.) as well as the conditions under which they occur.

Number of Platoon System Failures

Definition – This is the number of platoon system failures expressed as a ratio (e.g., per 1,000 miles driven).

Interpretation & Use(s) – This performance measure captures how often the truck platooning system fails (e.g., 10 failures/ 1,000 miles driven in platoon mode). Examples of truck platoon system failures include failure in coordinated braking between leading and following trucks, V2V communication signal loss, RF interference, malfunctioning radar/lidar, and others. High prevalence of truck platooning system failures may lead to driver disaffection regarding the usage of the platooning system and may lower driver acceptance of the technology. This performance measure can be categorized based on various conditions including weather, roadway geometry, surrounding roadway environment (e.g., metallic environments may cause RF interference), etc.

Data Needs – Data elements required include platoon system data (e.g., number of truck platooning system failures, truck trip miles, GPS traces), roadway data (e.g., grades, curvature, etc.), and other external conditions such as weather, traffic regimes, etc.

Evaluation Approaches – The analysis involves summarizing the rate of platoon system failures based on factors such as weather conditions, traffic regimes, roadway characteristics, and others.

Challenges – The main challenge in estimating this performance measure is the technical ability to log/collect the needed truck platoon system data (e.g., number of truck platooning system failures, truck trip miles, GPS traces, etc.) and external conditions data (e.g., weather, roadway, traffic regimes, etc.) during field deployment.

S-004: Performance measure(s) should capture the overall reliability of the truck platoon system under different conditions as experienced.

Truck Platoon System Reliability

Definition – Fraction of time/distance that the truck platoon system can be used during a trip when desired.

Interpretation & Use(s) – This measure provides an estimate of the overall reliability of the truck platooning system. Reliability could be compromised as a result of numerous technical system failures. Therefore, the truck platoon system may not always be used, even when desired, due to the absence of perfect reliability. However, the reliability of the truck platoon system must be acceptable enough under different conditions (e.g., weather, roadway geometry, lighting conditions, etc.) to enable its acceptance and adoption by truck drivers and fleet operators.

Data Needs – Data elements required include truck platooning system data (e.g., system failure logs, duration of system failures, GPS traces) and external conditions data (e.g., weather, roadway geometry, lighting conditions, etc.). Truck platooning system reliability can be calculated as $1 - \frac{\text{fraction of time or distance platoon system has failure}}{\text{total trip time/distance}}$ and expressed as percentage.

Evaluation Approaches – Reliability of the truck platooning system can be summarized based on contributing factors such as weather conditions, roadway characteristics, lighting conditions, and others. Then, overall reliability can be calculated across all the contributing factors.

Challenges – The main challenge in estimating this performance measure is the technical ability to log/collect the needed truck platoon system data (e.g., number of truck platooning system failures, duration of system failures, etc.) and external conditions data (e.g., weather, roadway, lighting, etc.) during field deployment.

Truck Platoon System Availability

Definition – Number of truck trips dispatched with properly working platooning system divided by total number of truck trips dispatched, expressed as a percent.

Interpretation & Use(s) – This performance measure is similar to reliability and provides a numerical estimate of the share/proportion of fully functioning equipped trucks available to fleet operators.

Data Needs – The key data elements required are logs of truck platoon system condition reports and logs of truck dispatch information.

Evaluation Approaches – The ratio of truck trips with properly working platooning system to total number of truck trips dispatched can be analyzed on a periodic basis. For example, this can be analyzed monthly, quarterly, and for any time period consistent with the reporting frequency for fleet operators.

Challenges – The main challenge in estimating this performance measure is the ability to log/collect the needed data (i.e., truck platoon system condition log, truck dispatch log).

S-005: Performance measure(s) should capture truck driver fatigue (i.e., levels of drowsiness) under platoon and non-platoon modes using objective data.

Fatigue Levels/ Levels of Drowsiness

Definition – Fatigue levels/Levels of drowsiness is a range of numerical or qualitative classifications that explains a driver's level of alertness from hyper-alert to involuntarily asleep due to physical or mental exhaustion.

Interpretation & Use(s) – This performance measure captures how truck platooning impacts driver fatigue. Driving in a platoon presents challenges such as reduced forward vision of following trucks due to the small following gap. This may increase anxiety levels of following drivers which can eventually lead to increased or rapid fatigue as reflected in levels of drowsiness. The level of impact may vary for drivers of lead and following trucks; hence, the assessment should be done for both driver categories. Increased fatigue/drowsiness can be determined using different types of driver monitoring systems such as face camera data in which a PERCLOS measure (percent of time over a minute that the eyelid covers more than 80 percent of the eye) can be manually derived or through the wearing of smart non-video devices (e.g., electronic device for measuring brain activity) by drivers.

Data Needs – Depending on the driver monitoring system being used, key data elements required for this performance measure include driver camera data and smart monitoring device data.

Evaluation Approach – To assess the impacts of truck platooning on driver fatigue, fatigue level measurements recorded for each driver can be compared between episodes of non-platoon driving (baseline period or episodes of non-platooning during deployment period) and active platoon driving over similar road segments and similar periods (i.e., non-randomized with/without analysis or before/after analysis). Factors such as lapsed time since the start of a trip, cumulative time spent within a platooning episode, cumulative time spent platooning within a trip, and cumulative exposure to active platooning across trips can affect the fatigue levels. Therefore, evaluation of the impacts of truck platooning on driver fatigue can be conducted along these dimensions.

Challenges – The main challenge in estimating this performance measure is the cost involved acquiring and maintaining driver monitoring systems. In addition, monitoring drivers during trips may be seen as an invasion of privacy by some drivers. Consequently, getting driver buy-in for these monitoring systems can be a challenge.

S-006: Performance measure(s) should capture truck platoon driver attentiveness / vigilance (e.g., influence on distraction) using objective data that captures the temporal aspects.

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Average Length of Distracted Eye Glances/ Percent of Time Eye Glances Away from Driving Task

Definition – This is a measure of the amount of driver attentiveness over a specified period.

Interpretation & Use(s) – This measure seeks to determine if a driver’s engagement in the platooning activity results in changes in the level of attentiveness/distraction that is normal during non-platoon driving. When drivers are inattentive, they may engage in tasks that are not directly related to the control of the truck. For example, drivers may divert their gaze to other tasks in the cabin (cell phones, radio, tablet, or laptop computer) that may not directly relate to driving. Also, changes in driver attentiveness during particularly monotonous episodes of driving may be manifested by mind wandering in which the driver’s thoughts shift away from the driving task. Drivers of lead trucks typically drive in manual mode (and sometimes in ACC) and have the highest responsibility of dictating how the platoon performs compared to the following drivers who are required to monitor surrounding traffic until they take over longitudinal/lateral control (or both) from the system. Therefore, the attentiveness performance measure is more critical for drivers of the following trucks than the lead trucks.

Data Needs – Key data elements required include time-stamped face-camera video data, time-stamped driving mode of truck, and other external conditions such as lighting, weather, and others.

Evaluation Approach – Driver attentiveness measures can be compared between non-platooning (i.e., baseline period or episodes of non-platooning during deployment period) and active platooning episodes for the same driver on similar roadway and times (i.e., non-randomized with/without analysis or before/after analysis). A more rigorous approach could be the comparison of driver attentiveness measures between drivers of platoon trucks and control trucks that are experiencing the same driving conditions (i.e., quasi or randomized experimental design). Factors such as lapsed time since the start of a trip, cumulative time spent within a platooning episode, cumulative time spent platooning within a trip, and cumulative exposure to active platooning across trips can affect attentiveness levels of drivers. Therefore, evaluation of the impacts of truck platooning on driver attentiveness can be conducted along these dimensions.

Challenges – The main challenge in estimating this performance measure is the cost involved acquiring and maintaining driver monitoring systems. In addition, monitoring drivers during trips may be seen as an invasion of privacy by some drivers. Consequently, getting driver buy-in for these monitoring systems may be a challenge. Another challenge is the cost of having control trucks driving within the proximity of the platoon trucks.

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 and the conditions under which they occur.

Rates of Crashes, Near-Crashes, Crash-Relevant Conflicts (including safety-critical events) Between Platoon Trucks

Definition – Rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between trucks in the platoon.

Interpretation & Use(s) – These performance measures seek to capture the level of safety of trucks that travel in platoon mode under different conditions. It is important to ensure that the interactions between the trucks that constitute a platoon are safe. This type of safety is fundamental to the adoption of truck platooning technology and must be guaranteed before dealing with the safety of

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interactions that involve surrounding traffic. Thresholds should be defined to enable the identification of safety critical events that involve longitudinal decelerations, time to collision, speed constraints, swerving in lane, aggressive lateral or lane deviations, etc. Other potentially hazardous events can be identified by reviewing recorded video footages. Also, activation of any of the available driver warning systems (e.g., lane departure, forward collision) when trucks are operating in platoon mode should be considered as safety critical events.

Data Needs – Key data elements required to estimate these performance measures include police reported collisions between trucks in a platoon, platoon trucks driving data (e.g., decelerations, aggressive lane/lateral deviations, time to collision values, driver warnings, gap settings, driving mode, platoon truck GPS traces, etc.), recorded video footage, and external environmental conditions such as weather, traffic regimes, roadway grade, etc.

Evaluation Approach – Rates of crashes, near-crashes, and crash-relevant conflicts between trucks in a platoon can be compared between episodes of non-platooning (i.e., baseline period or non-platooning periods during the deployment period) and active platooning for similar roadways and times (i.e., non-randomized with/without analysis or before/after analysis). Since safety is likely to be influenced by individual driver behavior, summarizing the relative rates of these conflicts by conflict type and environmental condition can first be performed within driver and then summarized across drivers.

Challenges – One of the key challenges is defining what constitutes near-crashes and crash-relevant conflicts since there is no universally agreed standard definition. Another key challenge in estimating these safety performance measures is the technical ability and the cost involved in collecting and analyzing all the driving data, recorded video footages, and external conditions data.

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.

Rates of Crashes, Near-Crashes, Crash-Relevant Conflicts (including safety-critical events)

Definition – Rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and unequipped cut-in vehicles.

Interpretation & Use(s) – These performance measures seek to capture the level of safety of the interactions between platoon trucks and unequipped vehicles that attempt to cut-in between platoon trucks under different conditions. It is important to ensure that the platoon system can safely detect and respond appropriately to unequipped cut-in vehicles. The gap settings of truck platoon systems, lane of travel of truck platoons, proximity of truck platoons to entry/exit ramps, and other factors may affect the likelihood of unequipped vehicles cutting in between platoon trucks. Regardless of the prevailing factors or environmental conditions, truck platoon systems must be able to safely interact with unequipped cut-in vehicles. Thresholds should be defined to enable the identification of safety critical events that involve longitudinal decelerations, time to collision, speed constraints, aggressive lateral or lane deviations, etc. Other potentially hazardous events can be identified by reviewing recorded video footages.

Data Needs – Key data elements required to estimate these performance measures include police reported collisions between platoon trucks and unequipped cut-in vehicles, platoon trucks' driving data (e.g., decelerations, time to collision values, driver warnings, gap settings, cut-in flags, driving mode, platoon truck GPS traces, etc.), recorded video footage, and external environmental conditions such as weather, traffic regimes, roadway grade, etc.

Evaluation Approach – Rates of crashes, near-crashes, and crash-relevant conflicts involving platoon trucks and unequipped cut-in vehicles can be compared between episodes of non-platooning (i.e., baseline period or non-platooning periods during deployment period) and active platooning for similar roadways and times (i.e., non-randomized with/without analysis or before/after analysis). Since safety is likely to be influenced by individual driver behavior, summarizing the relative rates of these conflicts by conflict type and environmental condition can first be performed within driver and then summarized across drivers.

Challenges – A key challenge is defining what constitutes near-crashes and crash-relevant conflicts since there is no universally agreed standard definition. Another key challenge in estimating these safety performance measures is the technical ability and the cost involved in collecting and analyzing all the driving data (especially for cut-in vehicles), recorded video footages, and external conditions data.

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).

Rates of Crashes, Near-Crashes, Crash-Relevant Conflicts (including safety-critical events)

Definition – Rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and surrounding traffic, excluding unequipped cut-in vehicles.

Interpretation & Use(s) – These performance measures seek to capture the level of safety of the interactions between platoon trucks and surrounding traffic, excluding unequipped cut-in vehicles under different conditions. It is important to ensure that truck platoon technology does not compromise the safety of surrounding traffic. Safety critical events such as lane departures and emergency braking involving platoon trucks can present safety concerns to surrounding traffic. Thresholds should be defined to enable the identification of safety critical events that involve longitudinal decelerations, time to collision, speed constraints, swerving in lane, aggressive lateral or lane deviations, etc. Other potentially hazardous events can be identified by reviewing recorded video footages.

Data Needs – Key data elements required to estimate these performance measures include police reported collisions between platoon trucks and other traffic (excluding unequipped cut-in vehicles), platoon trucks' driving data (e.g., decelerations, time to collision values, driver warnings, gap settings, cut-in flags, driving mode, platoon truck GPS traces, etc.), recorded video footage, and external environmental conditions such as weather, traffic regimes, roadway grade, etc.

Evaluation Approach – Rates of crashes, near-crashes, and crash-relevant conflicts involving platoon trucks and surrounding traffic (excluding unequipped cut-in vehicles) can be compared between episodes of non-platooning (i.e., baseline period or non-platooning periods during deployment period) and active platooning for similar roadways and times (i.e., non-randomized with/without analysis or before/after analysis). Since safety is likely to be influenced by individual driver behavior, summarizing the relative rates of these conflicts by conflict type and environmental condition can first be performed within driver and then summarized across drivers.

Challenges – A key challenge is defining what constitutes near-crashes and crash-relevant conflicts since there is no universally agreed standard definition. Another key challenge in estimating these safety performance measures is the technical ability and the cost involved in collecting and analyzing all the driving data (especially for surrounding vehicles), recorded video footages, and external conditions data.

S-010: Performance measure(s) should capture the following truck's compliance with the system-defined minimum safe following gap considering truck load and roadway grade.

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Minimum Gap Compliance Rates

Definition – Frequency with which a following truck in platoon mode falls below the system-defined minimum gap, expressed as a rate (e.g., per 1,000 miles).

Interpretation & Use(s) – Trucks in a platoon, by design follow each other using a system-defined minimum safe following gap calculated based on truck speeds, braking performance, and other factors. This performance measure is intended to measure how following trucks consistently observe the minimum safe following gap under varying conditions. Following truck load conditions and roadway environment (e.g., roadway grade) can affect maintenance of the system-defined minimum gap. For example, if a minimum system-defined gap for a truck platoon system is 0.8 seconds, this performance measure will capture the number of times the gap between the lead and following platoon trucks falls below 0.8 seconds.

Data Needs – The key data elements required to calculate this performance measure include truck speeds, system-defined minimum gap, recorded gap values during active platooning, following truck loading levels, truck GPS traces, truck trip miles, and external conditions such as roadway grade, weather, traffic regimes, etc.

Evaluation Approach – Since this performance measure is primarily evaluating how the platooning system is managing longitudinal control during platooning episodes, driver behavior will not directly influence this measure. Consequently, this measure will pool compliance rates across following trucks without distinguishing between drivers. Compliance rates can also be compared between different load levels of following trucks as well as between platooning on relatively flat roadway segments and segments with grades.

Challenges – The key challenge in estimating this safety performance measure is the technical ability to collect the needed data, including platoon driving data and external conditions data.

S-011: Performance measure(s) should capture instances where platoon system initiates unnecessary collision avoidance (i.e., false positives).

Rates of Unnecessary Emergency Braking (false positives)

Definition – Frequency of inappropriate braking actions by following trucks while in active platooning, expressed as a rate (e.g., per 1,000 miles driven)

Interpretation & Use(s) – A truck platooning system's primary control function is to regulate headway between leading and following trucks. It does this by modulation of the throttle or by braking. Consequently, the main avoidance response of the platooning system involves braking. Since it is often paired with an automatic emergency braking (AEB), it may in some circumstances respond to a forward target that is mistakenly detected in the immediately forward lane, but which may actually be in an adjacent lane. This can happen on small-radius curvy roadways. Thus, AEB initiation might occur when no conflicting target is present. This performance measure seeks to capture such false positives. For drivers of platoon trucks to have confidence in the system, the occurrence of such false positives must be significantly low.

Data Needs – Key data elements required to estimate this performance measure includes counts of inappropriate braking events either from driver reports or automated AEB braking event logs, truck driving mode, gap settings, GPS traces of trucks, time of occurrence of braking events, and external conditions such as weather, traffic regimes, lighting conditions, etc.

Evaluation Approach – Counts of unnecessary braking events can be tallied across all following trucks and compared across different external conditions such as weather, lighting conditions, etc.

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Challenges – The key challenge in estimating this safety performance measure is the technical ability to collect the needed data, including platoon driving data and external conditions data.

S-012: Performance measure(s) should capture the accuracy with which the platoon trucks maintain the system's current set/target following gap(s) considering truck load and roadway grade.

Target Gap Compliance Rate

Definition – Frequency with which a following truck in platoon mode falls below the target gap, expressed as a rate (e.g., per 1,000 miles driven).

Interpretation & Uses – This performance measure evaluates the degree to which truck platooning systems maintain target gaps that have been defined based on prevailing conditions such as roadway grade, load levels of following trucks, trucks speeds, etc. Although this performance measure is similar to the performance measure in requirement S-010, there is a difference in the gap values. The target gap of a platoon system (which is the threshold gap for this performance measure) is the instantaneous gap value set by the platoon system as a result of prevailing conditions; this gap value may change as a result of prevailing conditions. Conversely, system-defined minimum gap of a platoon system (the threshold gap for the performance measure in S-010) is the gap value defined based on field and controlled testing and does not change regardless of prevailing conditions. It is the absolute minimum gap (i.e., the closest a following truck can get to a leading truck) and it is always less than or equal to the target gap.

Data Needs – The key data elements required to calculate this performance measure include truck speeds, target gap records, actual gap values during active platooning, following truck loading levels, truck GPS traces, truck trip miles, and external conditions such as roadway grade, weather, traffic regimes, etc.

Evaluation Approach – Since this performance measure is primarily evaluating how the platooning system is managing longitudinal control during platooning episodes, driver behavior will not directly influence this measure. Consequently, this measure will pool compliance rates across following truck drivers without distinguishing between drivers. Compliance rates can also be compared between different load levels of following trucks as well as between platooning on relatively flat roadway segments and segments with grades.

Challenges – The key challenge in estimating this safety performance measure is the technical ability to collect the needed data, including platoon driving data and external conditions data.

Root Mean Square Error (RMSE) of Distance Tracking

Definition – Difference between actual distance to leading truck and desired following distance based on target gap setting.

Interpretation & Uses – This performance measure seeks to capture the magnitude of the error in maintaining required target distance between lead and following trucks under varying conditions. For drivers and fleet operators to have confidence in truck platooning technology and embrace its adoption, the magnitude of this distance tracking error must be significantly small. A closely related measure that can be used to capture similar information is the maximum and minimum error of distance tracking.

Data Needs – Key data elements required to estimate this measure include target gap and actual gap values during active platooning, driving mode, following truck loading levels, truck GPS traces, truck trip miles, and external conditions such as roadway grade, weather, etc.

Evaluation Approach – Since this performance measure is primarily evaluating how the platooning system is managing longitudinal control during platooning episodes, driver behavior will not directly influence this measure. Consequently, RMSE values can be compared across following trucks without distinguishing between drivers. RMSE values can also be compared between different load levels of following trucks as well as between platooning on relatively flat roadway segments and segments with grades.

Challenges – The key challenge in estimating this safety performance measure is the technical ability to collect the needed data, including platoon driving data and external conditions data.

2.3 Mobility

Impacts of truck platooning on mobility (e.g., congestion and traffic flow) have been reported in many simulation studies and field experiments (11) (12). However, these studies are for limited controlled testing and do not cover varying roadway, weather, and operational conditions. The multi-state, long-haul field test of truck platooning operations provides an opportunity for a broader mobility impacts assessment. The requirements and corresponding key performance measures for assessing the mobility impacts of truck platooning field deployment are discussed below.

M-001: Performance measure(s) should capture differences in travel time/travel time reliability of truck trips under platooning and non-platooning modes.

Travel Time/ Travel Time Reliability

Definition – Travel time is the total duration of travel to reach a target destination from an origin location. Travel time reliability is the degree of variability (or repeatability) in the total time taken to reach a destination across repeated trips to the same destination.

Interpretation & Use(s) – In most intelligent transportation (ITS) deployments, travel time is often used to measure improvements in trip durations (i.e., reduction in travel times) and trip reliability (i.e. improved predictability in travel times). As a result, most people tend to associate its use with capacity or operational improvements. However, within the context of truck platooning, the use of travel time is not intended to measure improvements. When trucks are coupled to form a platoon, they are expected to stay together during the course of the trip. When one platoon truck is pulled over for inspection, the other platoon truck(s) may have to wait, depending on the nature of the fleet operations. This interaction with law enforcement personnel may increase the duration of trips for those platoon trucks that were not pulled over. Secondly, depending on the mechanical properties (e.g., engine capacity) of platoon trucks, old platoon trucks with less efficient engine capabilities may slow down other relatively new truck(s) in the platoon that have high engine capacities. Consequently, travel time is used to assess whether trip durations will increase for platoon trucks. Similarly, fluctuations in trip durations and how it affects on-time arrival performance for platoon trucks can be measured using travel time reliability.

Data Needs – Key data elements required for this performance measure include platoon truck GPS traces, trip durations data, on-time performance data, total amount of active platooning during trip, and external conditions data such as weather, traffic regimes, trip route data, roadway data, etc. Travel time will be estimated as total time between trip origin and destination.

Evaluation Approach – To assess the impact of truck platooning on travel times and travel time reliability, estimates can be compared between baseline period trips (i.e., trips without platooning technology) and deployment period trips (i.e., trips with platooning technology in use, even if for only a

portion of the trip). This comparison must be done for the same route, origin/destination pair, similar weather conditions, similar traffic conditions, and the same driver or a driver with similar experience. A more superior and robust approach is to have both platoon and control trucks dispatched at about the same time and the differences in their arrival times at the destination recorded to make the comparison. This latter approach mitigates the impacts of confounding factors better and may produce a relatively more accurate comparison.

Challenges – The key challenge in estimating this performance measure is the technical ability to collect the needed data as well as the cost of having a control truck deployed alongside platoon trucks (assuming a quasi or randomized experimental is used). If the field deployment has a fleet operator partner, then getting a control truck to be dispatched around the same time as platoon trucks will be an operational challenge because it may disrupt dispatch schedules.

M-002: Performance measure(s) should capture impacts of truck platoon on tactical behavior of surrounding traffic under different conditions (e.g., grades, travel lane, weather, etc.) encountered during trip.

Rate of Overtaking Maneuvers (By surrounding vehicles)

Definition – Number of vehicles behind platoon trucks in the same travel lane that change lane, accelerate, and re-enter the former travel lane ahead of platoon trucks, expressed as a rate (e.g., per 1,000 platoon miles driven).

Interpretation & Use(s) – This performance measure seeks to understand driving behavior of vehicles that travel behind platoon trucks in the same lane. Information from this performance measure will help to understand whether such vehicles continue to drive normal when they are behind platoon trucks or they tend to initiate lane changes and re-enter the initial lane. Re-entering the initial lanes is an indication of drivers who are fine with driving in the same lane as platoon trucks but only when they are in front. Additionally, re-entering of the initial lanes implies more lane changing maneuvers that may have safety consequences. The relative speed of the overtaking vehicles can also be measured.

Data Needs – Key data elements required to estimate this measure includes side-facing radar measurements and camera footage, platoon trucks' driving mode and GPS traces, and external conditions data such as traffic regimes, weather, lighting conditions, roadway characteristics, etc.

Evaluation Approach – To assess the impacts of truck platooning on surrounding traffic behavior, comparison of the rate of overtaking maneuvers recorded during non-platooning (i.e., baseline period or non-platooning episodes of deployment period) and active platooning periods (i.e., deployment period) can be made. To account for the effects of confounding factors, the comparison should be made for the same travel route, weather conditions, traffic regimes, lighting conditions, and other environmental factors.

Challenges – The main challenge in estimating this performance measure is the technical ability and cost of collecting and processing side-facing radar and camera data, as well as external conditions data.

Rate of Lane Change Maneuvers (By surrounding vehicles)

Definition – Number of lane changing maneuvers executed by vehicles behind platoon trucks in the same and in adjacent lanes, expressed as a rate (e.g., per 1,000 platoon miles)

Interpretation & Use(s) – Similar to the rate of overtaking maneuvers, this performance measure also captures the driving behavior of vehicles within the immediate vicinity of platoon trucks. However,

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this measure focuses on all lane changing behaviors that occur for vehicles in adjacent lanes and behind platoon trucks in the same lane. The rate of occurrence of these lane changing maneuvers has potential negative impacts on safety and stability of traffic flow. Therefore, it is important that such behaviors are captured and understood, so that appropriate truck platooning operating principles can be formulated.

Data Needs – Key data elements required to estimate this measure includes side-facing radar measurements and camera footage, platoon truck driving mode, platoon truck GPS traces, and external conditions data such as traffic regimes, weather, lighting conditions, roadway characteristics, etc.

Evaluation Approach – To assess the impacts of truck platooning on surrounding traffic behavior, comparison of rate of lane change maneuvers by surrounding vehicles recorded during non-platooning (i.e., baseline period or non-platooning episodes of deployment period) and active platooning periods (i.e., deployment period) can be made. To account for the effects of confounding factors, the comparison should be made for the same travel route, weather conditions, traffic regimes, lighting conditions, and other environmental factors.

Challenges – The main challenge in estimating this performance measure is the technical ability and cost of collect and processing side-facing radar and camera data, as well as external conditions data.

Frequency/Number of heavy vehicles Behind Platoon* (7)

Definition – The frequency and number of heavy vehicles (especially trucks) that travel immediately behind platoon trucks in the same lane during active platooning, expressed as a rate (e.g., per 1,000 platoon miles driven).

Interpretation & Use(s) – During active platooning, there exists the possibility of non-equipped trucks driving immediately behind platoon trucks and ultimately increasing the platoon length. Such occurrences can influence the driving behavior of surrounding traffic as a result of the length of the platoon. Therefore, this performance measure seeks to capture how often these instances occur as well as the number of unequipped trucks involved.

Data Needs – The key data elements required include side/back-facing radar and camera data, platoon truck driving mode and GPS traces, and external conditions data such as traffic regimes, weather, lighting conditions, and other environmental factors.

Evaluation Approach – The frequency/number of heavy vehicles behind platoon trucks can be compared between non-platooning periods (i.e., baseline period or non-platooning episodes during deployment period) and active platooning periods (i.e., deployment period) for the same travel route and similar external conditions such as weather, traffic regimes, lighting conditions, and other environmental factors.

Challenges – The main challenge in estimating this performance measure is the technical ability and cost of collecting and processing side/back-facing radar and camera data, as well as external conditions data.

Average Number of Stopped Vehicles on Acceleration Lanes Due to Platoons* (7)

Definition – This is the average number of vehicles forced by platooning trucks to stop on the acceleration lane as they seek to join mainline traffic.

Interpretation & Use(s) – Vehicles from on-ramps attempting to join mainline traffic may be forced to stop on the acceleration lane due to the presence of platooning trucks in the first mainline lane. This performance measure is intended to capture the average number of vehicles that stop on the acceleration lane as a result of truck platooning. It is important to capture this measure because

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stopped vehicles on the acceleration lane will have difficulty accelerating and safely entering the mainline traffic flow. Also, stopped vehicles on the acceleration lane may lead to on-ramp queues and spillbacks to surface streets (especially when there are many lengthy truck platoons in the mainline traffic).

Data Needs – Key data elements required include acceleration lane vehicle stops from roadside cameras or rear/side facing cameras mounted on platooning trucks, the lengths and number of truck platoons in mainline traffic (especially first mainline lane), and external conditions such as traffic regimes, weather, lighting conditions, etc.

Evaluation Approach – Average number of stopped vehicles on acceleration lane can be compared between non-platooning periods (i.e., baseline or non-platooning episodes of deployment period) and active platooning periods (i.e., the deployment period) for the same route and similar external conditions.

Challenges – The key challenge in estimating this measure is the technical/financial ability to collect and process roadside and platoon-mounted camera data, as well as external conditions data.

Average Traffic Speed/Volume on Adjacent Lanes

Definition – This the average speed and count of vehicles in the immediate lanes (i.e., left and right lanes) adjacent to the travel lane of platooning trucks.

Interpretation & Use(s) – This measure seeks to understand the traffic flow parameters in the lanes adjacent to truck platoon lanes. Specifically, this measure focuses on the average speed and count of vehicles in the adjacent lanes. This information will help to understand speed homogeneity/heterogeneity between platooning trucks and surrounding traffic as well as potential variations in lane utilization between lanes used by platooning trucks and adjacent lanes.

Data Needs – Key data elements required to estimate this measure includes side-facing radar measurements and camera footage, platoon truck driving mode, platoon truck GPS traces, and external conditions data such as traffic regimes, weather, lighting conditions, roadway characteristics, etc.

Evaluation Approach – To assess the impacts of truck platooning on surrounding traffic behavior, comparison of average speed/volume of adjacent lanes traffic recorded during non-platooning (i.e., baseline period or non-platooning episodes of deployment period) and active platooning periods (i.e., deployment period) can be made. To account for the effects of confounding factors, the comparison should be done for the same travel route, weather conditions, traffic regimes, lighting conditions, and other environmental factors.

Challenges – The main challenge in estimating this performance measure is the technical ability and cost of collecting and processing side-facing radar and camera data, as well as external conditions data.

M-003: Performance measure(s) should capture traffic flow impacts of truck platoons on deployment corridor under different conditions.

Average Vehicle Throughput

Definition – Average number of vehicles that traverse a section of roadway within a specified period of time (e.g., vehicles per hour).

Interpretation & Use(s) – Trucks in platoon mode are expected to be tightly coupled together at smaller following gaps that enables consistent longitudinal (and lateral behavior); as a result, they are able to absorb the instabilities in traffic flow, dampen shockwave formation, and ultimately improve

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Truck Platooning Early Deployment Assessment– Independent Evaluation: Performance Measures for

traffic throughput. This measure seeks to quantify the potential increase in overall vehicle throughput as a result of truck platoons.

Data Needs – Key data elements required to estimate this measure includes platoon truck driving mode, platoon truck GPS traces, surrounding vehicle traffic/driving behavior, and external conditions data such as traffic regimes, weather, lighting conditions, roadway characteristics, work zones, etc.

Evaluation Approach – Multiple approaches can be used to assess the impacts of truck platooning on vehicle throughput. A microsimulation model that incorporates truck platooning operations and surrounding traffic/driving behavior can be used to evaluate the impacts of truck platooning on average vehicle throughput using a before/after or with/without analysis. An important feature of microsimulation models is the ability to control for the effects of confounding factors by incorporating them into the model. Another evaluation approach is to measure vehicle throughput in road segments that have recently been traversed by platooning trucks and comparing with vehicle throughput in the same areas measured minutes prior to the platoon trucks traversal. The temporal proximity of the sampling strategy ensures that environmental factors (e.g., weather, traffic regimes, construction areas, etc.) are shared across the two-comparison condition (i.e., presence versus absence of platooning trucks).

Challenges – The main challenge in estimating this performance measure is the technical ability and cost of collecting and processing side-facing radar and camera data to obtain surrounding traffic behavior, technical ability to simulate truck platooning technology and surrounding traffic behavior, as well as the availability of ITS data collection devices on traversed routes to measure vehicle throughput.

2.4 Energy and Emissions

One of the most promising benefits of truck platooning is energy savings (i.e., fuel savings) and reduction in truck vehicle emissions. The underlying idea is that trucks traveling in proximity would experience less aerodynamic drag and as a result consume less energy, depending on following distance (13) (14). Consequently, reductions in fuel use can lead to potential reductions in emissions. The requirements developed for performance measures and the corresponding performance measures that capture the impacts of truck platooning on energy use and emissions are presented below.

EE-001: Performance measure(s) should capture changes in fuel use due to truck platoons under different gap settings, truck configurations, load levels, and external conditions using objective data as experienced during trip.

Fuel Consumption Rate

Definition – The amount of fuel used by platoon trucks during trips, expressed as a rate (e.g., per 1,000 platoon miles driven).

Interpretation & Use(s) – With trucks in a platoon traveling at closer gaps, the effect of aerodynamic drag may be reduced and eventually lead to reductions in fuel use. This performance measure is intended to measure the impacts of truck platoons on fuel consumption under conditions experienced during trip (e.g., platoon mode status, varying gap settings, truck configurations, loading levels, and external conditions). This performance measure will enable fleet operators to determine if there is a business case for adopting truck platooning technology.

Data Needs – Key data elements required to estimate this measure include time-stamped platoon truck driving data such as fuel injector/use data, fuel flow meter data, platoon driving mode, platoon trucks GPS traces, platoon gap settings, loading levels, truck configurations, and external conditions data such as traffic regimes, weather, lighting conditions, roadway characteristics, work zones, etc.

Evaluation Approach – Multiple approaches can be used to assess the impacts of truck platooning on fuel consumption rate. A quantitative comparison can be made between fuel consumption rate estimates measured during non-platooning period (i.e., baseline period or non-platooning episodes during deployment period) and corresponding estimates measured during active platooning periods (i.e., during deployment period). To account for the impact of confounding factors in this approach (i.e., before/after analysis or with/without analysis), the comparison should be done for the same route, similar roadway characteristics, weather conditions, traffic regimes, and other environmental conditions. A more powerful and rigorous evaluation approach is the use of a control truck traveling within proximity of platoon trucks (i.e., quasi or randomized experimental design). In this approach, fuel consumption rates will be estimated for both control and platoon trucks; then, a quantitative comparison would be made between both estimates to ascertain the impacts of truck platooning on fuel use. Regardless of the adopted evaluation approach, the analysis should investigate how fuel consumption rates change with variations in loading levels, truck configurations, gap settings, weather conditions, traffic regimes, lighting conditions, and other environmental factors. Also, fuel savings as a result of platooning may not be the same for both lead and following trucks; therefore, the analysis should consider the distribution of fuel savings between lead and following trucks.

Challenges – The main challenge in estimating this performance measure is the technical ability of collecting and processing fuel consumption data as well as external conditions data.

EE-002: Performance measure(s) should capture changes in emission levels due to truck platoons under different gap settings, truck configurations, load levels and external conditions.

Emission Rates

Definition – The amount of fuel emissions from platooning trucks during trips, expressed as a rate (e.g., per 1,000 platoon miles driven).

Interpretation & Use(s) – With trucks in a platoon traveling at closer gaps, the effect of aerodynamic drag may be reduced and eventually lead to reductions in fuel use and fuel emissions. This performance measure is intended to measure the impacts of truck platoons on fuel emissions under conditions experienced during trip (e.g., platoon mode status, varying gap settings, truck configurations, loading levels, and external conditions). The pollutants to be considered include Nitrogen oxides (NO_x), Carbon dioxide (CO₂), Particulate matter (e.g., PM_{2.5}), Sulfur dioxide (SO₂), and others.

Data Needs – Key data elements required to estimate this measure includes time-stamped platoon truck driving data such as fuel injector/use data, fuel flow meter data, emission sensor data ,platoon driving mode, platoon trucks GPS traces, platoon gap settings, loading levels, truck configurations, and external conditions data such as traffic regimes, weather, lighting conditions, roadway characteristics, work zones, etc.

Evaluation Approach – Multiple approaches can be used to assess the impacts of truck platooning on emissions. A quantitative comparison can be made between emission rate estimates measured during non-platooning period (i.e., baseline period or non-platooning episodes during deployment period) and corresponding estimates measured during active platooning periods (i.e., during deployment period). To account for the impact of confounding factors in this approach (i.e., before/after analysis or with/without analysis), the comparison should be done for the same route,

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similar roadway characteristics, weather conditions, traffic regimes, and other environmental conditions. A more powerful and rigorous evaluation approach is the use of a control truck traveling within proximity of platoon trucks (i.e., quasi or randomized experimental design). In this approach, emission rates will be estimated for both control and platoon trucks; then, a quantitative comparison would be made between both estimates to ascertain the impacts of truck platooning on emissions. Regardless of the adopted evaluation approach, the analysis should investigate how fuel consumption rates change with variations in loading levels, truck configurations, gap settings, weather conditions, traffic regimes, lighting conditions, and other environmental factors.

Challenges – The main challenge in estimating this performance measure is the technical ability of collecting and processing fuel consumption data as well as external conditions data.

2.5 Fleet Operator and Truck Driver Impacts

During the steady-state cruising phase of truck platooning system with SAE Level 1 automation capabilities, driver performance will mostly consist of steering performance while travelling at shorter following gaps. Because drivers of following trucks have reduced visibility of the roadway ahead due to the shorter following gaps, it is possible that a truck driver's steering workload will be increased — especially in curves — leading to more rapid fatigue and decreased vigilance over time. For truck platooning technology to be accepted by truck drivers, they need to be educated on the capabilities of the specific truck platooning implementation as well as the potential additional driving responsibilities. In addition to impacts of truck platooning on truck drivers, fleet operators may have to adjust their daily operations (e.g., loading multiple trucks at a time to enable them depart depot/warehouse at the same time) to accommodate some of the requirements needed for commercial truck platooning to be effective. The requirements for performance measures and corresponding performance measures that capture the impacts of truck platooning on fleet operators and truck drivers are presented below.

FLT-001: Performance measure(s) should capture impacts of truck platooning on Fleet Operators daily operations.

Dispatch Time

Definition – The amount of time required to schedule the departure of trucks from a terminal or depot.

Interpretation & Use(s) – Adopting truck platoon technology may affect the daily operations of fleet operators. For example, the coordination and scheduling of the departure of two or three platoon trucks may present new challenges to dispatchers and logistics managers. This performance measure seeks to capture these potential additional tasks fleet operators may face in terms of their dispatching activities. For truck platooning technology to be adopted by fleet operators, it should have minimal impacts on the daily dispatching process.

Data Needs – Key data elements required for this performance measure include logs of truck dispatching and driver assignments, dispatching time, surveys and structured interviews of individuals involved in the dispatching process.

Evaluation Approach – To assess the impacts of truck platooning on the dispatching process, estimates of dispatch times for single or non-platoon trucks will be compared with corresponding platoon trucks dispatch times for similar routes per trip. If a control truck would be deployed as part of the field deployment, then the comparison of dispatch times can be made between the control and platoon trucks.

Challenges – The main challenge in estimating this performance measure is getting accurate data on dispatching process and dispatch times from fleet operators.

Logistics Cost

Definition – This is the general costs associated with the daily dispatching process.

Interpretation & Use(s) – Adopting truck platoon technology may affect the daily operations of fleet operators. For example, getting two trucks loaded and ready to leave a terminal at the same time may require increased labor and other resources which may ultimately result in extra operational cost. This performance measure seeks to capture these potential extra costs (e.g., labor costs, platoon technology maintenance costs, etc.) fleet operators may incur in organizing platoon operations. For truck platooning technology to be adopted by fleet operators, the extra cost in organizing platoon operations should be minimal.

Data Needs – Key data elements required for this performance measure include surveys and structured interviews of individuals involved in the dispatching process as well as daily cost information.

Evaluation Approach – To assess the impacts of truck platooning on the cost of dispatching process, estimates of dispatch costs for single/non-platoon trucks will be compared with corresponding platoon dispatch costs for similar routes.

Challenges – The main challenge in estimating this performance measure is getting accurate information on daily dispatching costs.

FLT-002: Performance measure(s) should capture cost savings to fleet operators due to fuel efficiency gains.

Fuel Savings

Definition – This is the cost savings due to reduction in fuel use as a result of truck platooning. It may be expressed as a rate (e.g., per 1,000 miles).

Interpretation & Use(s) – With trucks in a platoon traveling at closer gaps, the reduced effect of aerodynamic drag is expected to lead to reductions in fuel use. The reduction in fuel use is cost savings to fleet operators as platoon trucks will travel longer distances using a relatively smaller quantity of fuel. This performance measure seeks to capture the potential cost savings.

Data Needs – Key data elements required for this performance measure include fuel consumption rate under varying conditions from EE-001 and fuel cost information.

Evaluation Approach – To assess the impacts of truck platooning on fuel savings, measured estimates of fuel savings during non-platooning periods (i.e., baseline period or non-platooning episodes during platooning period) can be compared with corresponding estimates during active platooning periods for similar/same routes and similar external conditions such as weather, traffic regimes, lighting, roadway characteristics, and other environmental factors. A more rigorous approach is to compare fuel savings estimates for control and platoon trucks which travel within proximity of each other.

Challenges – The main challenge in estimating this performance measure is getting accurate fuel consumption estimates from EE-001.

FLT-003: Performance measure(s) should capture impacts of training on truck platoon drivers' performance as well as Fleet Operators operations.

Perceived Impacts of Driver Training on Platoon Driving/ Fleet Operations

Definition – This is the perceived impact of how driver training on platoon technology affects driver performance on the road as well as fleet operations.

Interpretation & Use(s) – This performance measure seeks to understand how training of drivers on the use truck platooning technology affect their understanding, safe operation, and eventual acceptance of the truck platoon system. This performance measure will help to answer questions such as: do drivers understand that headway may increase with speed? do drivers understand the limits of the vehicle’s braking authority and when their intervention is required? Also, this performance measure seeks to understand how training activities disrupt fleet operators’ operations. For example, the amount of time required for training sessions as well as the number of training sessions may prevent some drivers from embarking on trips or cause changes in already planned dispatch schedules.

Data Needs – Key data elements required for this performance measure include surveys and structured interviews with drivers and fleet operations personnel before/after training sessions and after trips.

Evaluation Approach – Responses from the surveys and interviews would be used to understand how the training activities affected platoon drivers’ understanding of the technology and road driving performance as well impacts on fleet operators’ operations.

Challenges – The main challenge is getting accurate survey and interview responses from platoon drivers and fleet operations personnel.

FLT-004: Performance measure(s) should capture how drivers adapt to the truck platoon system over time.

Adaptation in Platoon Driver Behavior

Definition – Observed changes in driver understanding and use of platoon technology with passage of time.

Interpretation & Use(s) – This performance measure seeks to capture the learning curve of truck platoon drivers as they become familiar with the technology. It looks at both positive and negative adaptations over time, thus, within trip (beginning vs. end of platoon trip), and longer term (when inexperienced with platoon system vs. after many platooning trips). Many metrics can be used for this performance measure, including both qualitative and quantitative. For example, the percent of highway driving time/distance spent in platooning mode will vary over time for drivers as they get used to the platoon system. Similarly, quantitative metrics such as number of platoon disengagements and platoon gap choices (assuming drivers have multiple gap options to choose from) would vary for a driver with time. The qualitative metrics will be gathered from surveys and structured interviews about drivers’ perceived adaptations regarding understanding and use of platoon technology (e.g., comfort level of using technology) over time. For negative adaptations, an example could be an increase in the rate of engaging in non-driving related activities over time as drivers get more comfortable and experienced at using truck platooning technology.

Data Needs – Key data elements required for this performance measure include truck platoon driving data (e.g., gap settings, GPS traces of platoon trucks, platoon miles traveled, driving mode, number of disengagements, etc.) surveys and structured interviews with drivers, and external conditions data such as weather, lighting, etc.

Evaluation Approach – Platoon drivers’ adaption to the technology can be evaluated by analyzing driving behavior metrics on a progressive timescale (e.g., one month, three months, and 6 months

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after exposure to platooning technology). To account for effect of confounding factors, analyses should be done for similar external conditions data such as lighting, weather, roadway characteristics, and other external factors.

Challenges – The main challenge in estimating this measure is the technical ability to collect truck platoon driving data, external conditions data, as well as getting accurate survey/interview responses from drivers.

FLT-005: Performance measure(s) should capture driver acceptance/satisfaction of/with truck platoon technology taking into account driver's position in the platoon.

Driver Acceptance/Satisfaction

Definition – A subjective rating of driver acceptance/satisfaction of/with truck platooning technology (e.g., on a scale of 1 to 10) as perceived considering the position of each driver in the platoon (i.e., lead truck vs following truck).

Interpretation & Use(s) – Drivers are key users of the truck platooning technology. Therefore, it is imperative that their views regarding acceptance of and satisfaction with the technology is captured. This performance measure seeks to do so. A high acceptance or satisfaction rate of truck platooning technology by drivers would be critical to the widespread adoption of truck platooning technology.

Data Needs – Key data elements required for this performance measure include surveys and structured interviews with drivers regarding issues such as platoon system's user interface, usability of the system, comfort with engagements and disengagements, preferences for position within the platoon and following gap settings, perception of the impact of platooning on workload/stress level, confidence in reliability and trust of the platoon system, and others.

Evaluation Approach – The main evaluation approach is to analyze survey and interview responses and pool them across drivers to obtain overall acceptance/satisfaction rate.

Challenges – The main challenge in estimating this measure is getting accurate survey/interview responses from drivers.

FLT-006: Performance measure(s) should capture Fleet Operators' acceptance/satisfaction of/with truck platoon technology.

Fleet Operator Acceptance/Satisfaction

Definition – A subjective rating of fleet operators' acceptance of or satisfaction with truck platooning technology (e.g., on a scale of 1 to 10).

Interpretation & Use(s) – Aside from drivers, fleet operators are one of the key users of the truck platooning technology. Therefore, it is imperative that their views regarding acceptance of and satisfaction with the technology is captured. This performance measure seeks to capture information about fleet operators experience with the platooning operation after field testing of the platooning system. A high acceptance or satisfaction rate of truck platooning technology by fleet operators would be critical to the widespread adoption of truck platooning technology.

Data Needs – Key data elements required for this performance measure include surveys and structured interviews with fleet operators regarding issues such as scheduling challenges, forming and coordinating platoon driving teams, safety concerns, preferences for platooning versus driving independently, impact of platooning on fleet operations personnel satisfaction, overall efficiency of the platoon system, and others.

Evaluation Approach – The main evaluation approach is to analyze survey and interview responses and pool them across fleet operations personnel to obtain overall acceptance/satisfaction rate.

Challenges – The main challenge in estimating this measure is getting accurate survey/interview responses fleet operators.

FLT-007: Performance measure(s) should capture how truck platoons affects driver behavior (e.g., highway following gap) in non-platoon situations.

Mean Gap/ Following Distance in Non-platoon Situations

Definition – This is the average time gap or following distance between the lead and following trucks when driving in manual mode during deployment or post-deployment period.

Interpretation & Use(s) – This performance measure seeks to understand how exposure to platooning will affect the driving behavior of drivers during non-platooning driving. Driving in a platooning configuration systematically differs from non-platoon driving such that the following truck drivers are exposed to shorter following headways for longer periods of time, than they would normally encounter during non-platoon driving. There is concern that this may acclimate drivers to short headways such that they become perceived as safe outside of the context of platooning (where the automation is in control of headway). Following too closely during manual mode is unsafe due to the relative slowness in human driver response to forward collision events. The behavioral change may be experienced immediately after transitioning from platooning driving to non-platooning driving during a trip or over a long period of time. This performance seeks to capture the behavioral changes in both time horizons.

Data Needs – Key data elements required for this performance measure include time-stamped driving mode, gap settings, GPS traces of platoon trucks, radar data, and appropriate external conditions data.

Evaluation Approach – To assess the potential carry over effect immediately following platoon disengagements, mean gap or following distance values immediately after disengagement can be compared with mean gap or following distance estimates prior to platoon disengagement for each driver. For long-term effect, mean gap or following distance values during non-platooning period (i.e., baseline period) for each driver can be compared with corresponding values estimated during post-platoon period (i.e., after the end of field deployment) to ascertain if the driver following behavior has been modified after extended period of exposure to truck platooning technology. Data obtained can be pooled across individual drivers to obtain a general behavior.

Challenges – The main challenge in estimating this measure is the technical ability to collect needed driving behavior data during platooning and non-platooning periods.

2.6 Infrastructure Impacts

Truck platooning may not be practical on all the different types of roadway infrastructure. It is important to identify infrastructure characteristics and requirements that would support safe and extended performance (i.e., ability to platoon on long continuous stretches of roadway) of truck platoons. Infrastructure characteristics such as facility types, roadway geometry (horizontal/vertical curves), number of lanes, dedicated lanes, speed limits, bridge crossing restrictions, and others, may influence the operational design domain of truck platoon systems. Therefore, it is important to determine infrastructure and roadway characteristics that may/may not permit safe and beneficial operation of truck platoons. Additionally, close following between trucks in a platoon and corresponding dynamic

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behavior (e.g., loading levels, acceleration, etc.) may affect the structural health of roadway infrastructure such as bridges (15) and pavements. The requirements for infrastructure impacts performance measures and corresponding performance measures are presented below.

II-001: Performance measures should capture the impact of truck platoon on bridge structures.

Maximum Stress Under Passage of Platoon* (16)

Definition – This is the maximum stress a bridge experiences due to the simultaneous loading of the weights of closely following platoon trucks at various lateral positions.

Interpretation & Use(s) – This performance measure seeks to understand how the characteristics of platoon trucks operations (e.g., platoon truck gap, axle spacing/loads, truck weight, load/trailer configurations, braking/acceleration profiles, etc.) as experienced, affect the structural health of bridges. Every bridge structure has its flexural strength (i.e., ability to resist deformation under load) (17); therefore, any loading that exceeds the flexural strength will lead to structural deformation of the bridge. It is important to know how bridge structures resist structural deformation as a result of stresses caused by truck platooning operations considering variations in load/axle configurations, gap settings, platoon length, and other factors.

Data Needs – Key data elements required for this performance measure include bridge stress data, relevant static truck characteristics (e.g., axle weight, gross vehicle weight, spacing between axles), and dynamic truck platoon configuration and driving data such as gaps between trucks, truck loads, driving speed of platoon, acceleration/deceleration and speed profiles, etc.

Evaluation Approach – To assess the impacts of truck platooning on the health of bridge structures, the maximum bridge stress experienced when occupied by platoons can be captured during the deployment period and compared with the corresponding bridge stress experienced by single truck operations during either baseline period or deployment period to understand how truck platooning affects the structural health of bridge structures.

Challenges – The main challenge in estimating this measure is the technical ability to collect needed truck driving and bridge stress data during platooning and non-platooning operations.

Changes in Bridge Lifespan and Lifecycle Costs* (16)

Definition – Changes in the average life span/ lifecycle costs of bridge structures as a result of truck platooning operations.

Interpretation & Use(s) – Subjecting bridge structures to stresses from platoon trucks operations can potentially lead to faster structural deterioration and eventual shortening of their lifespan. This performance measure seeks to capture potential decrease in the lifespan of bridge structures as a result of truck platooning. Another aspect of the impacts of truck platooning on bridge life span is the associated maintenance and lifecycle costs. As a result of potential rapid deterioration, the frequency and magnitude of maintenance costs may increase, leading to potentially higher lifecycle costs. Changes in both lifespan and lifecycle costs of bridge structures would be captured by this performance measure.

Data Needs – Key data elements required for this performance measure include bridge stress data, relevant static truck characteristics (e.g., axle weight, gross vehicle weight, spacing between axles), dynamic truck platoon driving data (e.g., gaps between trucks, driving speed of platoon, acceleration/deceleration and speed profiles) and maintenance cost data.

Evaluation Approach – To assess impacts on lifespan and lifecycle cost of bridge structures, bridge stresses data collected during truck platooning and non-platooning operations can be fed into bridge

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deterioration models to estimate potential reduction in bridge lifespan. Outputs from the bridge deterioration models can be combined with bridge lifecycle cost evaluation methods such as in NCHRP Report 483 (18) to estimate the lifecycle costs.

Challenges – The main challenge in estimating this measure is the technical ability to collect needed driving behavior and bridge stress data during platooning operations as well as maintenance cost data.

II-002: Performance measure(s) should capture information on infrastructure configuration/characteristics suitable for truck platoons and vice versa, as experienced during trip.

Percent of Highway Driving Time/Distance Spent in Platooning Mode Considering Infrastructure Configuration/Characteristics

Definition – Ratio of time spent, or distance travelled while in platoon mode compared with total trip hours or trip distance considering infrastructure configuration/characteristics.

Interpretation & Uses(s) – This performance measure reflects the usage rate of truck platoon technology during truck trips considering the prevailing infrastructural characteristics. The infrastructural characteristics include roadway grades, curve radii, average traffic speeds, traffic density, complex interchanges, presence of entrance and exit ramps with high vehicle activity (e.g., vehicles changing lanes and accelerating/decelerating to enter/exit highway), work zones, number and width of lanes, lighting conditions, and others. Essentially, this performance measure seeks to understand if there is any systematic relationship between infrastructure features and driver willingness to platoon as well as the extent of the system's ODD.

Data Needs – Data elements needed to estimate this performance measure includes log of truck driving mode (i.e., manual mode vs platoon mode), truck trip miles/time, GPS traces of platoon trucks, and external conditions data such as traffic regimes, roadway features (e.g., grade, number and width of lanes, presence of entrance and exit ramps, curve radii) as well as driver surveys.

Evaluation Approaches – Analyze platoon usage/driver survey data and summarize the infrastructure context within which platooning is active or disabled. This will help identify the infrastructure characteristics suitable to platoon driving.

Challenges – The main challenge in estimating this performance measure is the technical ability to log/collect the needed field data (e.g., truck driving mode, platoon trucks trip miles/time, GPS traces of platoon trucks, weather data, traffic regime data, infrastructure data, etc.) and obtain accurate survey responses that support observed platoon usage behavior.

II-003: Performance measure(s) should capture impacts of truck platoon on roadway pavements.

Accumulated Strain* (16)

Definition – This is the accumulation of strain in pavement structures due to short rest periods between load cycles induced by moving wheel load and live loads in platoon trucks.

Interpretation & Uses(s) – This performance measure seeks to capture the impacts of truck platooning on the structural health of pavement structures. The short gap between platoon trucks implies pavement structures do not have enough time to fully recover from the impacts of induced stresses from platoon trucks. Subjecting pavement structures to successive load cycles from tightly coupled platoon trucks with short rest periods between load cycles can potentially lead to strain accumulation that may eventually lead to faster structural deterioration, shortening of their lifespan, and increase in maintenance costs.

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Data Needs – Key data elements required for this performance measure include pavement accumulated strain data, relevant static truck characteristics (e.g., axle weight, gross vehicle weight, spacing between axles), and dynamic truck platoon configuration and driving data such as gaps between trucks, truck loads, driving speed of platoon, acceleration/deceleration and speed profiles, etc.

Evaluation Approaches – To assess the impacts of truck platooning on the health of pavement structures, the accumulated strain experienced by pavements when occupied by platoons can be captured during the deployment period and compared with the accumulated strain during non-platooning periods where trucks travel individually.

Challenges – The main challenge in estimating this measure is the technical ability to collect needed truck driving and pavement strain data during platooning and non-platooning periods.

Reduced Lateral Wandering* (16)

Definition – This is the reduction in lateral movement of platoon trucks in a lane during travel due to platoon trucks following the same wheel path.

Interpretation & Uses(s) – Vehicles tend to move laterally inside a travel lane (i.e., wandering) and do not maintain consistent lateral position during travel. The distribution of lateral positions of vehicles as they travel implies that stresses from vehicles are distributed across the pavement surface area (19). On the contrary, for platooning trucks with lane control (i.e., SAE level 2), the following trucks travel along the exact path of the lead truck. This phenomenon may lead to faster accumulation of pavement damage because of reduction in lane wandering and concentration of stress on the wheel paths of platoon trucks. This performance measure seeks to capture the potential reduction in lane wandering among platoon trucks. This information would be a useful input into pavement deterioration models and lifecycle cost assessments.

Data Needs – Key data elements required for this performance measure include relevant static truck characteristics (e.g., axle weight, gross vehicle weight, spacing between axles), and dynamic truck platoon configuration and driving data such as gaps between platoon trucks, truck loads, acceleration/deceleration and speed profiles, etc. In addition, lateral position data of platoon trucks from cameras mounted along sections of the roadway or mounted on research vehicles trailing platoon trucks will be needed. Similarly, data from sensors embedded in roadway pavements (e.g., pulses or signals due to platoon truck wheels) will also be needed. For truck platooning FOTs that involve in-service freight haulers, obtaining adequate data from embedded pavement sensors will be challenging due to potentially limited number of truck trips. Consequently, it will be more feasible to obtain such data from instrumented test tracks/facilities where multiple truck trips can be staged to enable adequate data collection.

Evaluation Approaches – To assess the impacts of truck platooning on lateral wandering, the lateral position data of platoon trucks can be analyzed to identify their travel paths and lane wandering distribution. The estimated lane wandering distribution can then be compared with established lane wandering distribution on pavements during non-platoon operations to determine if there is a reduction as a result of truck platooning technology.

Challenges – The main challenge in estimating this measure is the technical ability to collect needed truck driving data during platooning and non-platooning periods.

2.7 State and Local Government Impacts

Introduction of truck platoons on public roads implies possible changes to the way transportation systems are managed at the state and local levels from both an operational and law enforcement standpoint (e.g., following distance laws). Three requirements were initially developed for this key area. However, based on feedback from the Phase 1 Awardees and FHWA, the second requirement (SL-002) was removed. The requirements for performance measures with respect to the impacts of truck platooning and corresponding performance measure are presented below.

SL-001: Performance measure(s) should capture interactions between truck platoon drivers and law enforcement officials, such as regarding states' safe following distance laws.

Rate of Law Enforcement Pull-Overs

Definition – Number of times a platoon truck is pulled over by law enforcement, expressed as a rate (e.g., per 1,000 miles driven)

Interpretation & Uses(s) – This performance measure seeks to capture interactions between law enforcement officials and the platoon drivers during trips. Most states have following distance laws for trucks, and it is expected that deployment teams will choose routes whose safe following distances can be adhered to by their truck platoon system or may secure exemptions from observing following distance rules during deployment. Notwithstanding, there might be instances where law enforcement officials will mistakenly identify trucks in platoon mode as tailgating. This performance measure seeks to capture those interactions. There might be other restrictions of truck platoon travel on the roadway such as restricting the roads on which platooning is permitted, the travel lanes occupied during active platooning, or requirements to identify the platooning state of a truck. Any interactions between law enforcement officials and platoon drivers as a result of these other travel restrictions will be captured by this performance measure. Relatively higher interactions between platoon drivers and law enforcement officials compared to driving non-platoon trucks may impede acceptance of the technology by drivers.

Data Needs – Key data elements required for this performance measure include logs of law enforcement officials and platoon drivers interactions with details such as date and location of occurrence, posted speed limit, road type, type of enforcement agency, number of trucks stopped, duration of stop, outcome of the stop (e.g., ticket, warning, info exchange, curiosity), driving status (i.e., platooning or non-platooning mode), and others.

Evaluation Approaches – To assess the impacts, logs of interactions between platoon drivers and law enforcement officials will be analyzed. The analysis will differentiate between interactions that occurred when trucks were in platoon and non-platoon modes (i.e., with/without analysis) to determine if platooning induces more interactions between law enforcement officials and drivers. Similarly, rate of interaction between law enforcement officials and platoon drivers established during the baseline period (i.e., before field deployment began) or from historic data can be compared with interaction rates recorded for platooning trucks for similar route and roadway conditions (i.e., before/after analysis).

Challenges – The main challenge in estimating this measure is obtaining accurate and detailed records of platoon driver interactions with law enforcement officials for platooning and non-platooning operations. Another key challenge is that encounters with law enforcement officials may be very rare, leading to small sample data size.

SL-003: Performance measure(s) should capture impacts/differences (if any) in truck inspection and enforcements for truck platooning.

Truck Inspection Delay

Definition – The additional delay in inspection experienced by platoon trucks.

Interpretation & Uses(s) – Trucks usually undergo inspections at weigh stations during their trips. The inspection at the weigh station includes checking weight restrictions; checking equipment safety; and checking compliance with hours of service regulations. It is possible that trucks with platoon capabilities may receive extra attention at weigh stations during inspections. For example, it is possible that inspectors will take a relatively longer time to inspect the brakes of a platoon truck (especially the following truck) because of the shorter following gap. This performance measure seeks to capture this and any additional delays platoon trucks experience during inspections. Relatively longer inspection durations for platoon trucks will impede driver acceptance of the technology. If only one truck from a platoon was pulled over for inspection, the delay caused to the remaining platoon trucks will also be captured.

Data Needs – Key data elements required for this performance measure is the log of truck inspections with details such as duration of the inspection, number of trucks stopped, number of trucks in the platoon, and any other vital information provided by drivers.

Evaluation Approaches – To assess the impacts, logs of truck inspections will be analyzed for non-platooning periods (i.e., baseline period and periods of non-platooning episodes during deployment period) and active platooning. Comparison between these two will determine if platoon trucks do experience additional inspection delays.

Challenges – The main challenge in estimating this measure is obtaining accurate and detailed records of platoon truck inspections for platooning and non-platooning operations.

2.8 Vehicle Equipment Design Implications

As a new technology, truck platoon technology will require the acceptance of truck drivers and fleet operators/owners for it to be commercially viable. The acceptance includes (but is not limited to) ease of use of the truck platoon technology, truck driver comfort levels with the technology, reliability of the technology, etc. Based on these feedback, potential designs for improved safety, reliability, and effective performance can be considered. The requirements for vehicle equipment design implications performance measures and corresponding performance measures are presented below.

VED-001: Performance measure(s) should provide information regarding drivers' opinions on truck platoon equipment design deficiencies observed.

Vehicle Equipment Design Recommendations

Definition – These are design recommendations by platoon drivers based on experience acquired from using the technology.

Interpretation & Uses(s) – Users of technologies are often able to suggest useful improvement recommendations based on their experience with the technology and lessons learned. This performance measure is intended to capture all design recommendations that platoon drivers will suggest based on their experience with the truck platooning technology and lessons learned from its usage in the field deployment. The recommendations may revolve around usefulness of installed

devices, drivers' comfort with platoon operation, driver-vehicle interface design, safety of platoon technology, and others. These recommendations will help to make truck platoon technology safer, efficient, and user-friendly.

Data Needs – Key data elements required for this performance measure is the driver survey data and supporting technical data from platooning technology.

Evaluation Approaches – Summary of driver survey responses will point out the design improvements recommended by platoon drivers.

Challenges – The main challenge in estimating this measure is obtaining accurate/truthful survey responses from drivers.

VED-002: Performance measure(s) should capture the reliability of V2V communications between trucks in a platoon.

Rate of Communication Failures

Definition – Number of electronic communication failures (e.g., dropouts, failed connections) between each pair of trucks in a platoon, expressed as a rate (e.g., per 1,000 miles driven)

Interpretation & Uses(s) – This measure captures all communication failures experienced during field deployment. These include V2V communication dropouts between each pair of trucks in a platoon and handshake failures. This information will help to understand the reliability and availability of the truck platoon system. A more reliable truck platooning system is a pre-requisite for its acceptance and widespread adoption.

Data Needs – Key data elements required for this performance measure is the communication health status data between each pair of trucks in a platoon, dynamic driving data such as gap settings, position of a truck in a platoon, and external conditions data such as roadway grade, presence of RF transmitting structures, etc.

Evaluation Approaches – Summarize instances of communication failures and sort by key variables such as gap settings, roadway grade, roadway environment (e.g., rural vs urban), etc.

Challenges – The main challenge in estimating this measure is the technical ability to collect and process communication health status data as well as truck platooning driving data.

VED-003: Performance measure(s) should capture the effectiveness of information provided to drivers of following trucks (e.g., forward video streamed from lead to following truck, other DVI).

Usefulness of Information Received by Following Drivers

Definition – Following truck driver assessment of how received information aided in performing driving task.

Interpretation & Uses(s) – This measure is intended to capture following truck drivers' opinion on the usefulness of information sent to help them safely perform driving tasks. This may include forward video streamed from lead to following truck, voice communication between lead and following truck drivers, and other DVI functionalities. The comfort level of following truck drivers and the confidence with which they perform driving tasks will increase when provided with useful information about travel conditions ahead of them.

Data Needs – Key data elements required for this performance measure is driver survey data, including questions about differences based on position in platoon.

Evaluation Approaches – Analyze survey responses to determine usefulness of information received by following truck drivers.

Challenges – The main challenge in estimating this measure is obtaining accurate driver survey data.

2.9 Summary of Performance Measures from Outside Sources

As mentioned in the “Research Approach” section of Chapter 1, the performance measures discussed in this report were pulled from the Test and Evaluation plans proposed in this project (i.e., FHWA’s Truck Platooning Early Deployment project) as well as from other truck platooning field deployments and research efforts around the world. This section provides a summary of those performance measures that were obtained from sources outside of this project.

Table 2-1: Summary of Performance Measures from Outside Sources

Name	Definition	Source	Assigned Performance Measure Requirement
Rate of Interrupted Platoon Formation Attempts	Number of failed platoon formation attempts, expressed as a rate (e.g., per 1,000 miles).	Evaluation Approach for a Combined Implementation of Day 1 C-ITS and Truck Platooning - C-Roads Italy.	N/A
Speed Variation of Steady-State Platooning	Standard deviation of platoon truck speeds while in steady-state cruising mode.	Test and Demonstration Plan. D5.1 of H2020 project ENSEMBLE.	N/A
Frequency/Number of Heavy Vehicles Behind Platoon	The frequency and number of heavy vehicles (especially trucks) that travel immediately behind platoon trucks in the same lane during active platooning, expressed as a rate (e.g., per 1,000 platoon miles)	Evaluation Approach for a Combined Implementation of Day 1 C-ITS and Truck Platooning - C-Roads Italy	M-002
Average Number of Stopped Vehicles on Acceleration Lanes Due to Platoons	This is the average number of vehicles forced by truck platoon to stop on the acceleration lane as they seek to join mainline traffic	Evaluation Approach for a Combined Implementation of Day 1 C-ITS and Truck Platooning - C-Roads Italy	M-002
Maximum Stress Under Passage of Platoon	This is maximum stress a bridge experiences due to the simultaneous loading of the weights of closely following platoon trucks at various lateral positions	ENSEMBLE Work Package 4 Status Presentation	II-001
Changes in Bridge Lifespan and Lifecycle Costs	Changes in the average life span of bridge structures as a result of truck platooning operations.	ENSEMBLE Work Package 4 Status Presentation.	II-001
Accumulated Strain	This is the accumulation of strain in pavement structures due to short rest periods between load cycles induced by moving wheel load and live loads in platoon trucks.	ENSEMBLE Work Package 4 Status Presentation.	II-003
Changes in Lateral Wandering	This is the reduction in lateral movement of platoon trucks in a lane during travel due to platoon trucks following the same wheel path.	ENSEMBLE Work Package 4 Status Presentation.	II-003

3 Discussion on Other Considerations

The performance measures identified and discussed in this report are useful for conducting impacts assessment for truck platooning field deployments with similar goals and objectives as this project. However, to use these performance measures correctly, it must be within the appropriate context. In addition, some key considerations regarding field deployment evaluations must be taken into account. The sections below briefly discuss these contextual applications and key considerations.

3.1 Maturity of Truck Platooning Technology

Truck platooning technology has been in development for a long time. Germany ran initial tests of close following truck platooning on public roads in 1999, and publicly sponsored platooning research and development occurred during ensuing years funded by governments in Germany and Japan, the state of California, and the Federal Highway Administration (9). In recent times, truck platooning technology development has ramped up due to advancements in vehicle and communication technology as well as investments from the private sector. With the passage of time, the technology's functionality, reliability, and commercial viability improves.

Consequently, it is worth noting that the technology deployed in a particular field deployment is a version of the truck platooning technology with a set of functionalities clearly defined by its ODD. Any impacts evaluation of the field deployment using the performance measures presented in this report is an assessment of that specific version of truck platooning technology. Therefore, it is important to consider the maturity level of truck platooning technology when interpreting and drawing conclusions on field deployment evaluation results. For example, the fuel savings from a truck platooning field deployment is a function of the version of the technology that was deployed. Another deployment that uses a different version of truck platooning technology may have different fuel savings results.

In summary, the performance measures discussed in this report can be used to evaluate the impacts of truck platooning field deployments with similar goals and objectives as this project. They allow for broad and informed conclusions regarding important truck platoon research questions to be drawn. However, these performance measures are not intended to evaluate the version or maturity level of the specific truck platooning technology used in the deployment test as compared to some other version of truck platooning technology.

3.2 Truck Platooning Concepts

Many truck platooning implementation concepts have been proposed in the literature. At a minimum, the lead truck will be manually driven (some may have adaptive cruise control capabilities) while the following truck's longitudinal acceleration/deceleration (as well as lateral control for SAE Level 2 trucks) is controlled by the platooning system. Recently, there has been growing interest in the Auto-

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Follow concept. In this concept, the following truck operates at SAE Level 4 (i.e., there is no driver in the following truck) while the lead truck is driven manually (some may have some driver assistive systems). The platooning trucks in this concept will initiate and end their trips at strategically located platooning hubs alongside the roadway. Fuel savings combined with enhanced driver productivity in the lead truck and labor savings in the follower truck will greatly enhance return-on-investment (20). As a result, the Auto-Follow concept is becoming popular among fleet operators and platooning technology developers.

The performance measure requirements and corresponding performance measures developed in this project were specifically intended for a truck platooning field deployment involving similar trucks, with minimum SAE Level 1 automation capabilities, and both trucks having drivers behind the wheel. Accordingly, not all performance measure requirements or performance measures will be applicable to the Auto-Follow concept. Therefore, performance measures for assessing truck platoon field deployments should be selected considering the operational concept of the platoon system being deployed. The performance measure requirements and corresponding performance measures that may not be applicable to the Auto-Follow concept are presented below in Table 3-1.

Table 3-1: Performance Measure Requirements not Applicable to Auto-Follow Truck Platooning

ID	Requirements/Performance Measures	Reason(s)
OP-002	<p>Performance measure(s) should capture general behavior of trucks/drivers (e.g., speeding behavior, lane changing behavior, etc.) as they seek to form a platoon.</p> <p>Example Measures – Number of lane changes during platoon formation, Speed variability during platoon formation</p>	Platooning is formed at hub before entering roadway. No speeding or lane changing required
S-001	<p>Performance measure(s) should capture how often platoon system notifies (or fails to notify) truck platoon drivers it is no longer controlling longitudinal gap and/or lateral movement and the reason(s) for such notifications.</p> <p>Example Measure: Rate of longitudinal/lateral control dropout notifications</p>	There is no driver in following truck.
S-002	<p>Performance measure(s) should capture how often platoon drivers disengage platoon system control and the reason(s) for such disengagements.</p> <p>Example Measure: Rate of driver-initiated disengagements</p>	No platoon disengagement expected because there is no driver in following truck.
FLT-007	<p>Performance measure(s) should capture how truck platoons affects truck driver behavior (e.g., highway following gap) in non-platoon situations.</p> <p>Example Measure: Mean gap/following distance</p>	There is no driver in following truck.

ID	Requirements/Performance Measures	Reason(s)
VED-003	<p>Performance measure(s) should capture the effectiveness of information provided to drivers of following trucks (e.g., forward video streamed from lead to following truck, other DVI).</p> <p>Example Measure: Usefulness of information received by following truck drivers</p>	There is no driver in the following vehicle

3.3 Experimental Design

In order to have an accurate estimation of the true benefits/impacts of truck platooning in a field deployment, its impacts must be isolated from prevailing confounding factors. This can be achieved through a carefully planned experimental design. Regardless of the quality of selected performance measures, an inadequate experimental design can lead to flawed analysis and inaccurate representation of the performance of the truck platooning system. The next sections present a brief description of how to develop experimental designs for field deployments such as the truck platooning early deployment assessment project.

Hypothesis Formulation

The first step in developing an experimental design is the formulation of a hypothesis. A hypothesis is a specific statement which can be tested through statistical means by analyzing established or defined performance measures. It is essential for a field deployment to be designed with clearly defined hypotheses to aid in the interpretation of results. In formulating the hypothesis, consideration should be given to the data needed to evaluate the performance measures. It is vital that the data collected in a field deployment enable the hypotheses to be accepted or rejected. To do this, both the independent (i.e., causal factors) and dependent variables (i.e., performance measures of interest) should be well defined at the start of the field deployment (4). An example of a hypothesis for the truck platooning field deployment is “*Truck platooning trips will reduce fuel consumption compared to non-platooning truck trips.*”

Experimental Design

There are three main types of experimental designs that can be employed in evaluations of truck platooning field deployments. These are described below.

Non-Experimental Design

In this design, the impacts of the truck platooning system are assessed by examining changes in estimated performance measures between the baseline and after deployment periods. Ideally, the two periods would be equal lengths so that there is an opportunity in the baseline period for the same variations to occur that may occur in the deployment period (e.g., seasonal effects). The non-experimental design does not include a control group, making it the weakest study design. Without a control group, it is difficult to assess what would have happened in the absence of the truck platooning deployment. By design, it does not account for confounding factors, and does not control for other threats to internal validity, possibly leading to false conclusions. To control for the effects of

confounding factors, data for all possible known confounding factors must be collected and analyzed as part of the overall evaluation. Before/After studies and longitudinal studies are examples of such a design.

Within-Subjects Design

In a within-subjects design, each subject experiences all experimental manipulations. For example, in a truck platooning FOT, all platoon drivers may drive in both platooning (i.e., platooning system is active and engaged) and non-platooning (i.e., manual driving) scenarios during the deployment period. There are two main advantages of this experimental design:

- Fewer trucks and drivers are needed for the field deployment (implies lower deployment cost)
- Minimizes the impact of driver behavior influences on estimated benefits and impacts since the same drivers are used for both platooning and non-platooning operations.

A potential risk associated with this design is the risk for carry-over effects. That is, the experience of platooning may affect the behavior of a driver when driving in manual mode (e.g., driving at shorter gaps in manual mode). An example of this type of experimental design is the with/without analysis.

Between-Subjects Design

In a between-subjects design, each subject (i.e., truck driver) belongs to either the treatment (trucks equipped with platooning technology) or control (trucks without platooning capabilities) group. No driver can be part of both groups. The advantage in this type of design is the absence of carry-over effect as individual drivers belong to only a single group. However, this might require more trucks to be included in the experimental design and potentially increase cost. The two types of between-subject designs are described below.

Randomized Design

In randomized designs, study subjects (i.e., truck drivers) are randomly assigned to the control group (i.e., trucks without platooning capabilities) and the treatment group (i.e., trucks equipped with platooning technology). Data for each group are collected before (pre-test or pre-implementation) and during the deployment (post-test or post-implementation). At the end of the experiment, differences between the treatment and control groups can be attributed directly to the effect of the treatment (i.e., truck platooning), if the sample is large enough. Randomization ensures that the control and treatment groups are equivalent with respect to all factors other than whether they received the treatment (i.e., equipped or unequipped with truck platooning technology). Here, the control group serves as the “counterfactual” of what would have happened in the absence of the treatment, which is a key requirement in determining whether a treatment caused a particular outcome.

Quasi-Experimental Design

Quasi-experimental design approximates the randomized experimental design. Quasi-experimental designs use control and treatment groups, but assignment to the groups is non-random (unlike randomized experiments). The control and treatment groups cannot be assumed to be similar. Some efforts can be put into making the treatment and control groups similar. For example, a rule can be established that subjects in the control and treatment groups should have similar key characteristics such as similar driving experience level, similar age distribution of trucks, and others. Failure to identify

all the key characteristics may impact evaluation findings. Evaluation results from this design may not be conclusive since there may be a possible selection bias. Hence, the differences in the two groups must be assessed during the pre-test and accounted for in the analysis.

Sample Size and Power Analysis

Field deployments such as the truck platooning field deployment should be able to provide accurate estimates of the impacts of the technology. When the sample size (i.e., number of trucks and drivers, number of truck trips) is small, it will be difficult to statistically prove the impacts of the technology. With very large sample sizes, the chance of finding a statistically significant effect increases. However, that will require more subjects and test runs (i.e., trucks, drivers, and truck trips) which is expensive. To ensure that the right sample size is chosen, a power and sample size analysis must be conducted. The power of a test is the probability of correctly rejecting the null hypothesis when the null hypothesis is false. In other words, it is the likelihood that a field deployment will detect a deviation from the null hypothesis given that one exists. The minimum sample size required for a field deployment is a function of three main elements: 1) selected power of the test; 2) significance level; and, 3) expected difference in the effect size of each adopted performance measure (e.g. fuel consumption rates) between treatment and control group. For details on how to determine the appropriate sample size for a field deployment, please refer to FESTA Handbook Version 7 (4).

4 Conclusions

This report is an outcome of the Phase 1 IE's support to ITS JPO and its partner agencies (primarily FHWA and FMCSA) on the "Truck Platooning Early Deployment Assessment, Phase 1" project. The report includes:

- Synthesis of performance measures for evaluating truck platooning field deployments obtained from Phase 1 Awardees as well as from other truck platooning projects around the world;
- Discussion of experimental designs for truck platooning field deployments; and
- Contextual applications of the performance measures developed in this report.

While many performance measures have been presented in this report, the actual performance measures that will be used to evaluate the impacts of truck platooning technology in Phase 2 will be dependent on the Awardee's proposed evaluation plan as well as availability and quality of field data collected during the deployment period.

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