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Integrating Transformative Technologies in Indiana's Transportation Operations

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JOINT TRANSPORTATION RESEARCH PROGRAM

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NOTICE

COVER IMAGE

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16. Abstract

New and emerging transportation technologies, driven by automation, connectivity, and electrification, could potentially help address the transportation sector's persistent and pervasive problems associated with safety, mobility, energy use, and so on. For this reason, the state of Indiana, uniquely positioned to serve nationwide interstate truck traffic, seeks ways to identify and incorporate these new technologies on Indiana's highways. This report addressed the challenges and opportunities regarding the integration of transformative technologies in Indiana's truck operations, with particular focus on truck platooning. The report started with a review of current literature about disruptive technologies in general and truck platooning. This includes published information on the impacts of platooning on transportation outcomes—energy use, mobility, safety, truck operators' comfort, infrastructure condition/longevity, emissions, and other impacts. Regarding these impacts, the report summarizes existing simulation models for analyzing/evaluating truck platooning. Driver comfort, in terms of the platoon inter-truck headways, was investigated using a driving simulation study at Purdue University's Center for Connected and Automated Transportation Center (CCAT) Human Factors Laboratory. The report also identified and discussed opportunities and challenges to truck platooning. Next, the report presents a process developed for identifying truck-platooning sections, and a multi-criteria framework for ex poste or ex ante evaluation of platooning segments. Finally, the report discusses the future trends of freight transportation in Indiana (including the challenges and opportunities) in truck platooning policy and development.

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EXECUTIVE SUMMARY

Introduction

New and emerging transportation technologies, driven by automation, connectivity, and electrification, could potentially help address the truck transportation sector's persistent and pervasive problems associated with safety, mobility, energy use, and so on. For this reason, the state of Indiana, uniquely and strategically positioned to serve national interstate truck traffic, seeks ways to study, identify, and incorporate these new technologies on Indiana's highways.

Findings

This report addresses the challenges and opportunities of integrating the transformative technologies in Indiana's truck operations, with a particular focus on truck platooning. The report provides details on the impacts of platooning on transportation outcomes—energy use, mobility, safety, truck operators comfort, infrastructure condition/longevity, emissions, and other impacts. Regarding these impacts, the report presents simulation models for analyzing/evaluating truck platooning. Driver comfort, in terms of the platoon inter-truck headways, was investigated using a driving simulation study in the Center for Connected and Automated Transportation (CCAT) Human Factors Laboratory at Purdue University. This report also identifies and discusses opportunities and challenges of truck platooning. Next, the report outlines a process for identifying truck-platoonable sections, and a multi-criteria framework for *ex poste* or *ex ante* evaluation of platooning segments. Finally, the report discusses the future trends of freight transportation in Indiana (including challenges and opportunities) in truck platooning policy and development.

Implementation

The opportunities and challenges associated with truck platooning presented in this report could help serve as a baseline to inform INDOT policy on truck platooning and to identify prospective sections for truck platooning. The multi-criteria framework for the evaluation of platooning segments can help INDOT make decisions for prospective platooning programs (ex ante) or already-implemented programs (ex poste).

A core group of people at INDOT's multimodal and freight/logistics departments, under the advisement of FHWA, could define and select implementation strategies relative to the agency's practices regarding truck platooning. The principal mission of this implementing panel would be to advance and institutionalize the most practicable strategies and evaluation procedures for truck platooning as recommended in this research report.

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ACRONYMS

AD	Assisted Driving
ATA	American Trucking Association
CACC	Cooperative Adaptive Cooperative Control
CAT	Connected and Automated Trucks
CAV	Connected and Automated Vehicles
CFD	Computational Flow Dynamics (model)
DATP	Driver-Assisted Truck Platooning
FE	Finite Element
ICT	Information and Computer Technology
IOT	Internet of Things
HDV	Human-Driven Vehicle
MEPD	Mechanistic-Empirical Pavement Design
SAE	Society of Automotive Engineers
SPTP	(Highway) Segment Potential for Truck Platooning
TPP	Truck Platooning-Participation Percentage
TP	Truck Platoon
V2V	Vehicle-to-Vehicle Connectivity
V2X	Vehicle-to-Everything Connectivity

LIST OF TERMS

Cab-over design	A body style of truck that has a vertical front or flat face, with the cabin sitting above or forward of the front axle. Synonyms: cab forward (U.S.), flat nose (Canada), forward control (UK). In contrast, in conventional truck design, the engine is mounted in front of the driver.
Freight consolidation	Where several small-sized shipments that are all being sent to the same location to be bundled on a single truck and shipped to their destination.
Lateral safety	Safety of a vehicle relative to others in the adjacent lane.
Longitudinal safety	Safety of a vehicle relative to others in the same lane, of just upstream or downstream.
Platoonability	The suitability of a highway segment for truck platooning.
Platoon line lead	The truck that leads the platoon.
Platoon line tail	The truck at the tail end of the platoon.
Truck platooning participation	The percentage of trucks in a corridor that engage in platooning at a given time. In the literature, this term is often misnamed as “market penetration” of truck platooning.

1. INTRODUCTION

1.1 Study Background and Problem Statement

1.1.1 National Trends in Trucking

Supported by a robust network of interstate highway infrastructure, the United States is expected to see continued increase in its highway freight dependency over the next few decades. Indiana has several major interstate highways (including Interstate 65, Interstate 69, Interstate 70, and Interstate 74) that serve freight vehicles from all other regions of the nation and from Canada and Mexico.

1.1.2 Indiana's Tracking Industry

Indiana's critical role in national transportation delivery is evidenced by its strategic geographical location and the high freight volumes on its interstate highway network, which represents the arteries that keep commerce flowing within and across the state. The state's world-class transportation infrastructure provides companies with a competitive advantage in manufacturing and distribution, and the state's government intends to maintain this advantage. For industries in the state whose operations involve significant amounts of shipping, the importance of cost-efficient transportation cannot be overemphasized. Thanks to the state's highway network (and other modes that operate in tandem with highways), businesses can cost-effectively transport raw materials, commodities, components, and finished products to sites of production, transfer, or processing and to markets located in Indiana and outside. By 2040, Indiana's truck freight shipments will exceed several hundreds of billions in dollars.

Indiana's economic vitality and growth have been linked to the retention and growth of the industries that operate within the state and the attraction of new industries. The government of Indiana continues to provide incentives for business retention and attraction to the state. These initiatives include policies that reduce the cost of operations and enhance business productivity. The exploitation of emerging technologies for highway operations can be considered as one such initiative. Technology-based concepts that significantly reduce the overall shipping costs and reduce shipping time, can help reduce the overall operating costs of industries in the state which will ultimately translate into increased productivity and, consequently, increased output, increased employment, higher personal incomes, and expanded tax revenues. For this reason, Indiana continually seeks to enhance the efficiency of its interstates for the benefit of its customers.

1.1.3 The Indiana Department of Transportation (INDOT)'s Role and Responsibility Regarding Efficient Trucking

INDOT bears the responsibility to protect the billions of taxpayer dollars already invested in highway infrastructure by adopting policies that facilitate trucking operations and support the state's economic development. Increased truck travel leads to accelerated infrastructure degradation (Ashrafi et al., 2017; Murillo-Hoyos et al., 2014). Proper maintenance, rehabilitation, and repair strategies need to be in place to accommodate increasing volumes of truck traffic. As a result, it is increasingly important to address Indiana's highway asset management and operations associated with the rapidly growing freight volumes and the consideration of emerging technologies. Besides its impact on maintenance, increased freight activity necessitates additional enforcement and regulation. Sections of Indiana's highways have a no-truck policy on left-most or two left-most lanes for the safety and efficiency of passenger vehicles. Enforcing this policy is more difficult to achieve, and some trucks occupy restricted lanes at times. Projected increases in truck volumes over the next few decades may result in more trucks occupying restricted lanes, resulting in reduced safety, perceived safety, and general efficiency. The primary challenge is to enforce such regulations without reducing highway freight reliability (no late shipments, etc.) while maintaining desired safety and efficiency of all vehicles on the road.

Consistent with this quest, INDOT continually identifies promising and relevant new technologies for their possible deployment on the state's highways. In this regard, it can be beneficial for INDOT to acquire the perspectives of experts in INDOT (divisions of design, traffic operations, etc.) and in the shipping/carrier industry (including truck drivers), regarding the enabling technologies, human factors, operations, and impacts of new and emerging freight-related technologies. It is also expected that an investigation of the wider long-term transportation impacts of emerging freight-carrying disruptive technologies and practices (all road classes) and platooning (at freeways/interstates), in Indiana, could provide valuable information that could help INDOT properly and proactively plan to incorporate these technologies in the state's transportation systems management. Further, from a demand perspective, it is useful to make reliable projections of the future conditions of highway freight transportation and to identify favorable opportunities for Indiana and INDOT to capitalize on these projections. At the current time, the new technologies include electric propulsion, vehicle automation, and connectivity.

1.1.4 Promise of the New Transportation Technologies

Connectivity is enabled by information and communication science, and its applications include truck platooning (the concatenation of two or more trucks to form a convoy). Concatenation may be either planned by truck drivers themselves or may happen spontaneously on the road, with or without the aid of electronic connectivity between the trucks. The truck at the head of the line is the platoon "leader," and the platoon "followers" react and adapt to changes in the leader's movements. In electronic concatenation, the trucks follow each other closely at space intervals that are established using connectivity technology and automated driving support systems. A significant part of this study addresses the transportation system impacts of platooning.

Platooning has been targeted primarily towards freight transportation of heavy-duty vehicles (Alam et al., 2010; Nowakowski et al., 2015; Tsugawa et al., 2011). Published literature and recent results from real-life and simulation studies at Purdue's school of mechanical engineering address platooning entities (trucks) and some platoon operations, mostly in the context of control and communication. Recent research addressed platooning object formalization, platoon properties, and platoon operations (Maiti et al., 2017). However, relatively little work has been done to estimate the impacts of platooning on mobility, safety, and other metrics of transportation performance. The need for this research direction has been realized by several researchers (Deng, 2016). Therefore, this research study includes platooning impacts on highway transportation safety and mobility among others, and the evaluation is guided by truck-platoon simulation models.

1.2 Study Objectives

Using a literature review, this study sought to acquire the perspectives of experts and researchers on the impacts of truck platooning as the most promising freight-related new and emerging technology. The second part of the study based on a review of existing literature also examined the prospective challenges, opportunities, and benefits of electronic truck platooning in terms of roadway safety, mobility, energy consumption and emissions, driver (operator) comfort, and highway infrastructure (pavement and bridge) degradation. The study is intended to yield results that can serve as a basis for making policy on truck platooning. The study's original goals were to address transformative technologies in Indiana's transportation operations; however, this objective evolved towards a focus on truck platooning specifically, at the request of the study advisory committee. A list of the revised goals of the study is as follows.

- Review of current literature about truck platooning.
- Review simulation models that analyze or evaluate specific impacts of truck platooning.
- Identify and discuss opportunities and challenges to truck platooning.
- Assess some of the human-factor impacts of platooning: specifically driver comfort, in terms of the platoon inter-truck headways.
- Develop a decision-support framework for identifying truck-platoonable sections.
- Develop a multi-criteria framework for ex poste or ex ante evaluation of platooning programs.
- Discuss the future trends of freight transportation in Indiana, and the roles of technology paradigms and planning paradigms in truck platooning policy and development.

1.3 Organization of This Report

The study begins with an introductory chapter that discusses national trends in trucking and Indiana's contribution to national trucking, and role and responsibility of the Indiana DOT regarding efficient trucking. The promise of the new transportation technologies (automation and connectivity) is highlighted, and exploiting these opportunities is cast as a problem statement. This leads to the study objectives, followed by an outline of the report. In Chapter 2, a review of the literature on truck platooning is presented. This includes past work on platoon planning, platforms for platooning impact evaluation, and the various impacts of platooning (energy use, mobility, safety, truck operators' comfort, infrastructure condition/longevity, emissions, and other impacts. Chapter 3 presents existing simulation models for analyzing/evaluating truck platooning and Chapter 4 identifies and discusses opportunities and challenges to truck platooning. Chapter 5 discusses the methods and results of a driving simulation experiment that provided insights on platoon headways. Chapter 6 presents a decision-support framework for identifying truck-platoonable sections, and Chapter 7 presents a multi-criteria framework for ex poste evaluation of platooning programs. In Chapter 8, the study report discusses the future trends of freight transportation in Indiana, and challenges and opportunities. Chapter 9 concludes the study.

2. REVIEW OF THE LITERATURE ON TRUCK PLATOONING

2.1 Introduction

Platooning is an emerging vehicle technology that allows two or more vehicles, typically trucks, to travel together in convoys (Figure 2.1). This technology is facilitated through connectivity and automated driving support systems. The former can utilize dedicated short-range communications (DSRC) or newly emerging communication protocols, whereas the latter is a technology that is being actively developed. Using connectivity and automation, vehicles in the platoon automatically maintain a close distance between each other on the highways, sharing sensor data as well as performing collaborative driving tasks. The truck at the head of the platoon acts as the leader, with the middle vehicles and trailing vehicles reacting and adapting to changes in its movement using LIDAR and connectivity (communication) technologies.

With truck platooning deployment and operations, the potential benefits include improved safety, mobility, and efficiency, as well as improved fuel savings, reduced greenhouse gas emissions, and reduced operating costs for the commercial freight industry. In a subsequent section of this report, we provide a wider discussion of platooning impacts.

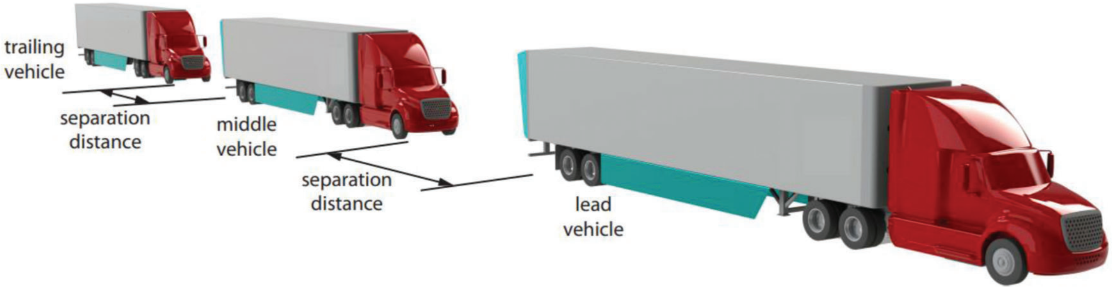


Figure 2.1 Basic schematic of a multi-truck platoon (McAuliffe et al., 2017).

2.2 Platoon Planning

Researchers have identified at least three categories of truck platooning.

1. *Prior-scheduled platooning:* All trips are announced before the start of the operations. Therefore, all platoon plans can be created in advance. This is often referred to as off-line or static planning.
2. *Enroute-scheduled platooning:* Truck operators announce their trips closely before departure or even when the trucks are en-route. Therefore, trip announcements arrive during the execution of the trips. This is often referred to as online or dynamic planning.
3. *Unscheduled platooning:* Trucks that are near each other form platoons on the road without any prior planning. This type of platooning is also referred to as spontaneous, ad-hoc or on-the-fly platooning.

Bhoopalam et al. (2018) addressed these categories using different terminology. Trucking is largely a private sector activity. However, as a public sector organization whose mission includes promotion of trucking operations, INDOT could help establish or supporting physical and cyber infrastructure. This can be achieved by including a central platooning support center, to facilitate scheduled or real-time platooning. Also, the state could offer incentives for trucks to engage in opportunistic platooning. However, in the era of autonomous transportation, any physical support center could quickly become obsolete or moved to a cloud platform where it could be accessed directly by the prospective platooning autonomous trucks with or without human input.

2.3 Platforms for Platooning Impact Evaluation

The impacts of truck platooning on energy use, safety, mobility, infrastructure deterioration/longevity, and so on, can be analyzed using at least one of the five platforms listed as follows (some of these are illustrated in Figure 2.2).

- Real life in-service road.
- Real-life test track.
- Physical simulation using wind tunnel micro-scale or large-scale.
- Computer simulation (microsimulation for impacts on mobility, energy; and driving simulation for impacts on safety, human factors).
- Questionnaire surveys and interviews, including anecdotal (experiential) evidence from truck drivers and operators.

2.4 The Various Impacts of Platooning

This section of the report examines the impacts of truck platooning on energy use, safety, mobility, infrastructure deterioration/longevity, and others. In these studies, platooning trucks were considered to be not autonomous.

2.4.1 Impact on Energy Use

2.4.1.1 Findings from the literature. The findings from the literature regarding platooning's impact on energy use (fuel savings) are as follows.

- Energy impacts are in the form of reduction in fuel use.
- Savings arise from the reduction in drag (Larson et al., 2015; Zhang et al., 2020).
- Savings vary by the vehicle position in the platoon (Figure 2.3): the middle vehicles save the most, followed by the trailing vehicle and the lead vehicle.
- Energy savings are dependent on platoon specifications (speed, spacing between vehicles).
- Energy savings increase (in a non-linear fashion) as the gap is reduced.
- Magnitude of savings generally ranges from 7% to 18%.
- 66% of total miles driven by large trucks could be "platooned."
- Grade percentage and travel speed can alter fuel savings.

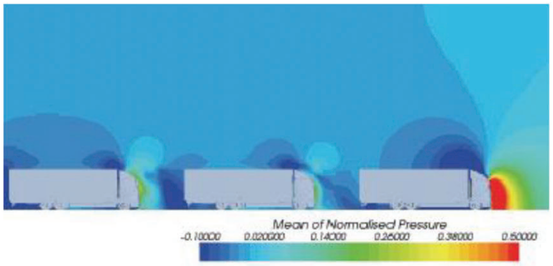
Table 2.1 presents a summary of the literature on the energy impacts of truck platooning.

2.4.1.2 Impact on energy use—case examples in Indiana. In Indiana, total fuel consumption by large trucks (Classes 8 and above) is 1.2 trillion gallons (Iyer et al., 2022). For specific location illustrations, two potential platooning locations were identified on I-65 and I-70, based on their cross-section features, pavement condition and truck flow. The proportion of trucks of the total traffic volume is 22%; total length of the identified prospective platooning sections is 20 miles. Based on the Annual Average Daily Traffic (AADT) data from the online Traffic Count Database System, and 365 days/year operations of the highway, their estimated energy savings are presented in

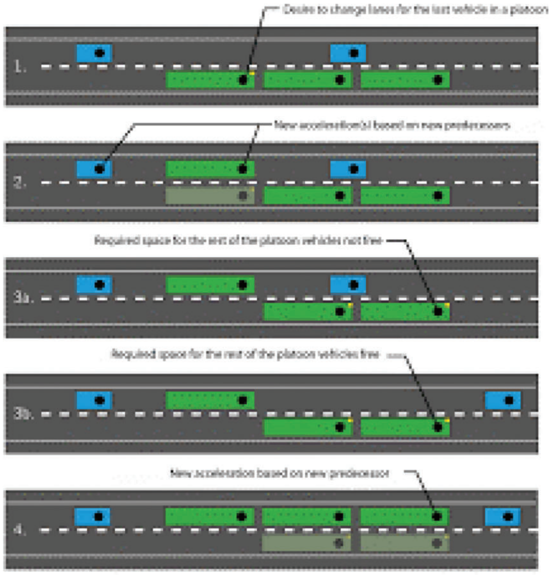
(a) Testing on in-service road (Peloton test) (FHWA, 2021)

(b) Testing on test track (Transport Canada, 2018)

(c) Testing in wind tunnel (Al Refai, 2019)



(d) Computer simulation (profile view) (Tsugawa et al., 2011)



(e) Driving Simulation Testing (Rutgers CAIT Spasovic Lab) (Spasovic et al., 2019)

(f) Computer simulation (layout view) (Faber et al., 2020)

Figure 2.2 Platooning testing and evaluation platforms.

Figures 2.4(a) and (b), respectively. The annual fuel saved is calculated using the following equation:

$$\begin{aligned} \mathit{Annual\ Fuel\ Saved} = \mathit{AADT} * \mathit{Days} * \mathit{Truck\ Percentage} \\ * \mathit{Averaged\ MPG\ of\ Trucks} \\ * \mathit{Total\ Platoonable\ Miles} \\ * \mathit{Fuel\ Saving\ Rate} \end{aligned}$$

The base AADT used for I-65 4.00 miles north of SR 267 is 73,132 vehicles/day; the base AADT used for I-70 1.00 mile east of SR 9 WIM 953600 is 42,320 vehicles/day.

2.4.2 Impact on Mobility

2.4.2.1 Findings from the literature. The findings from the literature regarding platooning impacts on mobility, are as follows.

- Mobility benefits become more obvious as more trucks in a corridor engage in platooning.

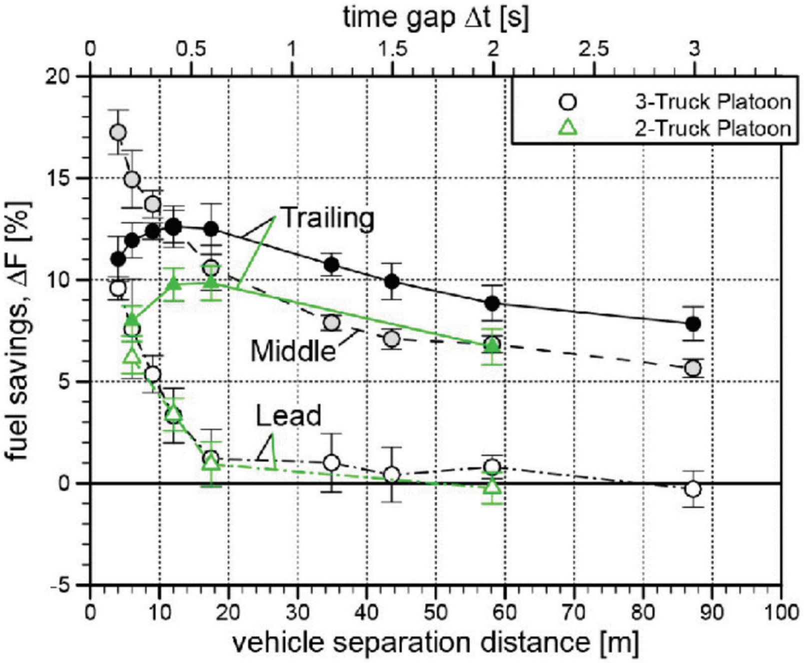


Figure 2.3 Individual-vehicle fuel-savings results for a three-vehicle platoon (McAuliffe et al., 2018).

- The relationship between truck platooning-participation (percentage) (TPP) in the platooning and capacity increase is non-linear.
    - 40% TPP: traffic flow greatly improves.
    - 60% TPP: most bottlenecks in corridor dissipate.
    - 100% TPP: 92% increase in capacity.
- Potential road capacity increase of 2% up to 19%.
- Longer platoons tend to impair freeway merging movements.

Using empirical and anecdotal evidence from trucking operators in Europe, a study by the European Automobile Manufacturers' Association (2016) determined that truck platooning reduces congestion by improving traffic flows and reducing tailbacks (long lines of stationary or slow-moving vehicles), therefore optimizing transport by using roads more effectively, helping deliver goods faster and reducing traffic jams. Table 2.2 presents a summary of the literature on the mobility impacts of truck platooning.

2.4.3 Impact on Safety

The findings from the literature regarding platooning impacts on safety, are as follows.

- Positive effect on longitudinal safety; but negative effect on lateral safety.
- Longitudinal safety: human error due to non-ideal reaction times, fatigue, distractions, etc. can be eliminated, thereby improving safety.
- Automated control of braking and accelerating reduces crash propensity, frequency, and severity.
- Carriers tend to place a high premium on safety benefits of platooning compared to other impacts.
- Safety impacts influenced significantly by platooning specifications and traffic conditions.
- Adverse safety impacts particularly imminent at merging and diverging areas of the highway.

Table 2.3 presents a summary of the literature on the safety impacts of truck platooning.

2.4.4 Impact on Truck Operators Comfort

The findings from the literature regarding platooning impacts on truck operators' comfort, are as follows.

- The effect on truck operator's comfort is bi-directional.
- Comfort is reduced where the operator has little trust in automation and is anxious about safety and to a lesser extent, travel efficiency and mobility.
- Comfort is enhanced where the operator has trust in automation.
- Comfort is also enhanced through platooning dynamics, for example, reduced jerk (sudden deceleration and acceleration).
- Platooning reduces most of the stress associated with stop-and-go driving.

Although traditional human-vehicle interface has been extensively explored, the paradigm shifted from the role of humans as drivers, to the role of passengers in electronic truck platooning. This requires a reexamination of explicit operator comfort and security in truck platooning. For example, applying inappropriate car-following distance may lead to operator's anxiety and the shift from human control to autonomous driving can trigger motion sickness. Table 2.4 presents a summary of

TABLE 2.1
Energy Impacts of Truck Platooning

Study #	General Context	Findings	Type of Experiment	References
1	Overall positive impact on fuel efficiency	In a TP, the lead vehicle saves up to 10%; middle vehicle up to 17%; and trailing vehicle up to 13%.	Real-life track experiments	The NREL Study Lammert et al., 2014
2	Technologies that improve energy efficiency	Efficient routing, cycle smoothing and adaptive control technologies.	Simulation + real experiments	NREL, Gonder et al., 2014
3	The case of two tandem trucks	The average fuel consumption saving to be achieved by tandem operation varies from about 11% at 3–4 meters spacing to about 8% at 8–10 meters spacing.	Real-life track experiments	Browand et al., 2004
4	CACC for truck platooning and energy saving	Fuel can be saved by about 15% when the gap was 4.7 m. A simulation study shows that the effectiveness of the platooning with the gap of 10 m when the 40% penetration in heavy trucks is 2.1% reduction of CO_2 along an expressway.	Real-life track experiments	Tsugawa et al., 2014
5	Relationship between headway and energy efficiency	Energy savings generally increased in a non-linear fashion as the gap was reduced. Middle truck saved the most fuel at gaps shorter than 12 m; trailing truck saved the most at longer gaps, while lead truck saved the least at all gaps.	Real world truck test	McAuliffe et al., 2018
6	Fuel savings from platooning aerodynamics	Significant correlation between multiple unaffiliated track studies, wind tunnel, and computational fluid dynamics (CFD) work, all indicating the same trend for fuel efficiency and gap.	Real world truck experiments	Lammert et al., 2018
7	66%–76% of total miles driven by large trucks could be "platooned"	Platoon of three Class 8 tractor-trailers under different driving conditions and gaps, reported fuel savings of 4%–5% for the leading truck and 10%–14% for the following trucks. Platoon of two Class 8 tractor-trailer. Fuel savings range from 3.7% to 6.4% (2.7%–5.3% for the lead tractor and 2.8%-9.7% for the trailing vehicle).	Test tracks	Lu & Shladover, 2014 Lammert et al., 2014
8	National fuel savings estimation	With these bounding assumptions, the widespread adoption of platooning operations for combination trucks in the United States could lead to a total savings of 1.5 billion gallons of petroleum derived fuels.	Real world data analysis	Muratori et al., 2017
9	Grade effects on two-truck platooning fuel savings	Fuel savings are uniform for 0% road grade and grade <1% uphill, increases in speed assist in the fuel savings by reducing aerodynamic drag force.	Simulation	Taylor et al., 2020

the literature on the impacts of truck platooning on truck operators' comfort. In the current study, a driving simulator experiment was carried out to investigate the impacts of vehicle-following headways on operator's comfort in the context of autonomous vehicles.

2.4.5 Impact on Bridge Infrastructure Condition/Longevity

The findings from the literature regarding platooning impacts on bridge condition/longevity, are presented as follows.

- Live loads due to truck platoons would subject the components of the superstructure and foundation to straining actions that are several times higher than allowed by their current load rating (Sayed et al., 2020) (Figure 2.7).
- The study by Yarnold and Weidner (2019) investigated the impact of platooning on the current design procedure with more focus on the impact of the following parameters: bridge span, span length, bridge configuration, and the number of trucks in the platoon. Results show that the *AASHTO Standard Specifications for Highway Bridge* are not safe to handle truck platoons in most cases.
- Tohme and Yarnold (2020) investigated the impact of the number of trucks in the platoon and the distance on three existing design methods: the Allowable Stress Design (ASD) method, the Load Factor Design (LFD) method, and the Load and Resistance Factor Design (LRFD) method. Their results showed the following.

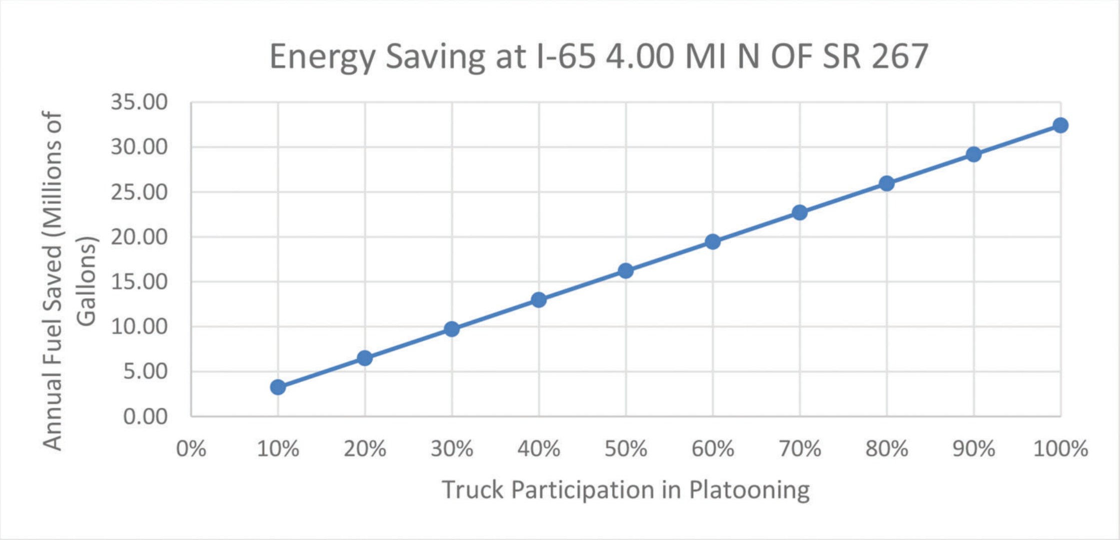


Figure 2.4 Anticipated energy impacts—truck platooning on a section of Interstate 65 for various traffic volumes.

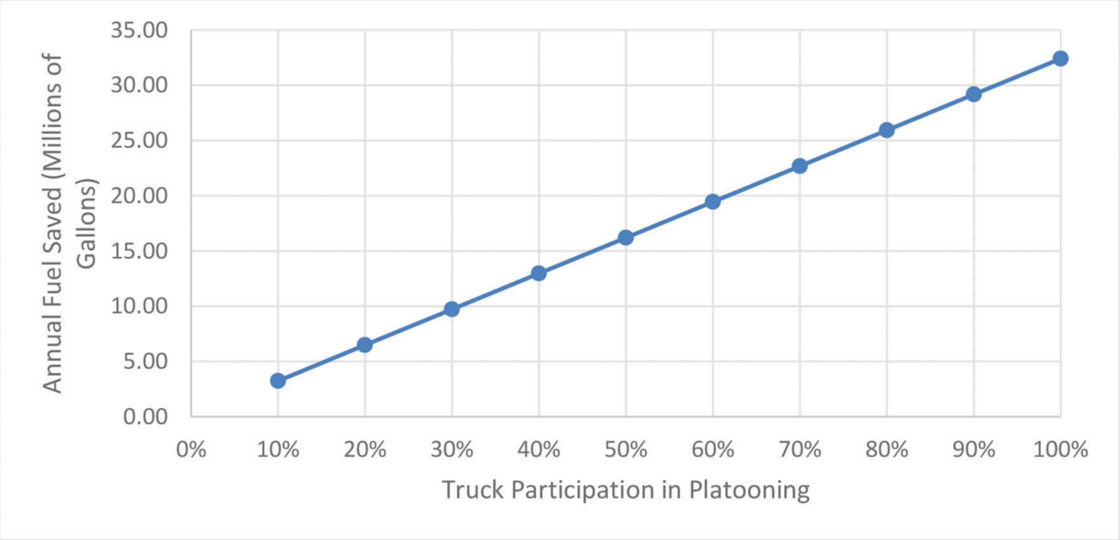


Figure 2.5 Anticipated energy impacts—truck platooning on a section of Interstate 70 for various traffic volumes.

  - The existing design methods are not appropriate to deal with truck platoons. In other words, these design guidelines are not safe if truck platoons use the bridges.
  - The number of trucks per platoon and the spacing between trucks in the platoon are major factors that affect the internal forces in the structure of the bridge. Thus, these old structures and the current design guidelines might become a restriction for the formulation of the platoon so further research is required to develop new standards that are able to deal with platoons.
- Kamranian (2019) evaluated the ability of the Hay River Bridge on handling truck platoons and investigated the impact of different truck platoon sizes: two trucks, three trucks and four trucks.
  - Their results show that the Hay River Bridge has adequate capacity for a platoon of two trucks. However, larger platoon sizes are unsafe and may cause failures.
- Two of the most comprehensive studies that analyzed the impact of different platoon characteristics on bridges are those by Birgisson et al. (2020) and Pillay (2020) in the Texas A&M Transportation Institute. They analyzed the performance of all bridges in the state of Texas under platooning using the National Bridge Inventory (NBI) database. They analyzed existing conditions and how bridges designed using different design methods (Allowable Stress Design (ASD) method, the Load Factor Design (LFD) method, and the Load and Resistance Factor Design (LRFD)) and construction material (concrete or steel) will perform under platooning. Additionally, the impact of the number of trucks in the platoon, truck type, and truck spacing on different bridges is conducted. Finally, the study offers a scheme for prioritizing bridges according to their conditions based on the bridge

TABLE 2.2
Mobility Impacts of Truck Platooning

Study #	General Findings	Specific Findings	Type of Experiment	Reference
1	Overall positive impact on mobility	Mobility benefits become manifest only when TP-MPR exceeds 80%	Computer (microscopic traffic) simulation	Lee et al., 2021
2	Positive impact on mobility, especially the road capacity	92% freeway pipeline capacity increase under 100% CACC market penetration	Microscopic traffic simulation	Liu et al., 2020
3	Positive impact in terms of traffic flow	Capacity improvement has a quadratic relationship with TPP. Traffic flow is greatly improved when the TPP is 40% or higher. For TPP above 60%, corridor bottlenecks can be almost eliminated.	Microscopic traffic simulation	Liu et al., 2018
4	Benefits of truck platooning in terms of travel efficiency	Faster delivery of goods; reduction of traffic jams and tailbacks; and improved traffic flow.	Anecdotal (experiential) evidence from trucking operators	Aarts & Feddes, 2016 & Euro Auto Manufacturers' Assoc., 2016
5	Pros and cons of truck platooning	Potential road capacity increase of 2%–19%. Large platoons impair merging movements on freeway	Simulation	Wang et al., 2019
7	Truck platooning benefit the travel efficiency	Significant travel time reduction of 0.5 secs platooning vehicle headways during peak-hr periods on a 5.3 mi section of I-85	Traffic simulation	Gordon, 2015
8	Cost and benefits of truck platooning	Platooning leads to higher capacity of truck lanes and higher traffic density at truck lanes; but reduced congestion overall.	Data analysis on existing database + case study	USDOT, 2018

TABLE 2.3
Safety Impacts of Truck Platooning

Study #	General Findings	Specific Findings	Type of Experiment	Reference
1	Reduction of total crash events	TP has +ve effect on longitudinal safety, but -ve effect on lateral safety.	Microsimulation	Yue et al., 2018
2	Significant safety improvements in some conditions	Minimum intensity of traffic safety is significantly enhanced via TP	Microsimulation	Yang et al., 2019
3	TP on mainline may be detrimental to traffic safety in high traffic intensity	Lots of uncertainty in the impact of TP w.r.t. safety and efficiency that depend on interaction among platoon, demand, and traffic	Microsimulation + control	Faber et al., 2020
4	Sensors onboard TP vehicles may improve general safety (speculative);	Surveys show carriers will adopt TP-capable vehicles if safety is not impeded; Adoption significantly affected by safety implications of TPs	Prototype field test	Bishop et al., 2014
5	Increased TPP increases longitudinal safety but reduces lateral safety	Platoon formulation algorithm for sequencing, platoon completion, and speed control	Microsimulation (using VISSIM)	Lee et al., 2021
6	Adverse impacts of platooning	Adverse impacts on safety are particularly felt at merging and diverging areas	Microsimulation	Yang et al., 2018
7	Impacts of platooning on safety	Analyzed lane-changing sequence, gap-creation ability, and lane-change desire modeling for TPs. Safety effect of different platoon specifications (lengths, headways, speed, deceleration, etc.)	Microsimulation	Faber et al., 2020
8	Added levels of autonomy reduces human error	Human error due to non-ideal reaction times, fatigue, distractions, etc. can be eliminated, thereby improving safety	Field testing	Cheek et al., 2020

TABLE 2.4
Impacts of Truck Platooning on Truck Operator's Comfort

Study #	General Findings/Objectives	Specific Findings	Type of Experiment	Reference
1	Investigated the applicability of a machine learning framework to assess driver comfort.	Inverse reinforcement learning method to learn personalized driving styles for self-driving cars from demonstration.	Real-world driving data for model training	Kuderer et al., 2015
2	Operators' comfort and awareness should be reconsidered when shifting from human control to autonomous driving.	–	Conceptual analysis	Elbanhawi et al., 2015
3	Driving simulator experiment was designed to investigate the impacts of car-following headways on operator's comfort in autonomous vehicles.	Thresholds of headways corresponding to different comfort levels were estimated. Results indicate that participants tend to choose smaller headways when the autonomous system were engaged.	Driving simulator experiment	Li et al., 2021

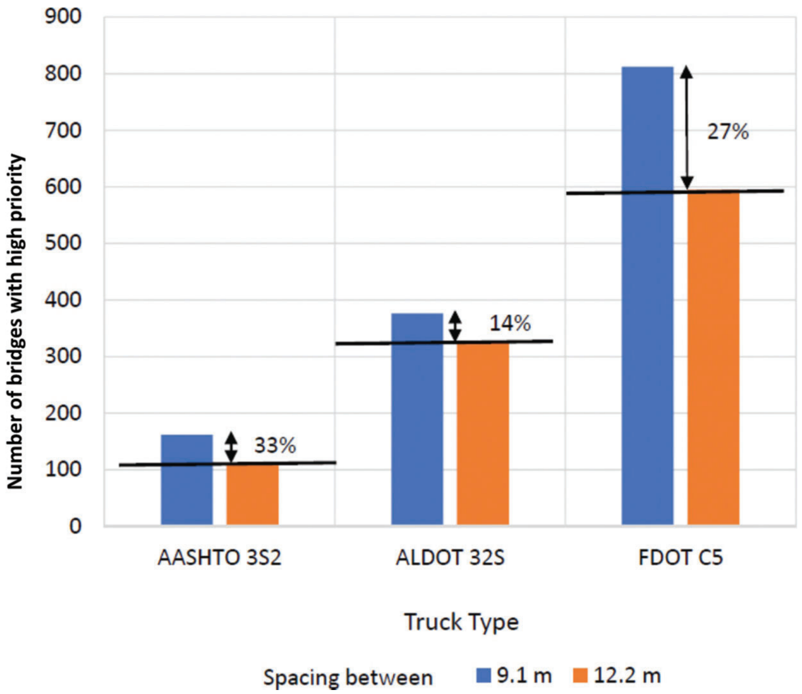


Figure 2.6 Number of bridges that need special attention for different truck types and truck spacing (Birgisson et al., 2020, Othman, 2021).

capacity and truck loads. Their results showed the following.

- The spacing between trucks is the most influential factor of bridge condition under platooning loads.
- For example, 33% increase in the number of bridges needing special attention when the truck spacing is increased from 30 ft to 40 ft. Figure 2.6 presents the number of bridges needing special attention, for different truck types and for 30-ft truck spacing and 40-ft truck spacing.

- Similarly, Thulaseedharan et al. (2021) investigated the impact of truck platooning on 3,000 bridges with different characteristics and prioritized these bridges using the same methodology mentioned in the previous two studies. The study showed the following.
  - The number of trucks in the platoon has a minor impact on the number of bridges with high priority. For example, results show a 7% increase in the number of bridges needing special attention when the platoon size increased from two trucks to three trucks.
  - The spacing between the trucks, on the other hand, is the major factor that affects the bridge performance. For example, a 68% increase in the number of bridges needing special attention was observed when the truck spacing was reduced from 9 m to 12 m, as shown in Figure 2.7.
  - Controlling the impact of the platoons on the bridges can be done by controlling the space between the trucks within the platoon.

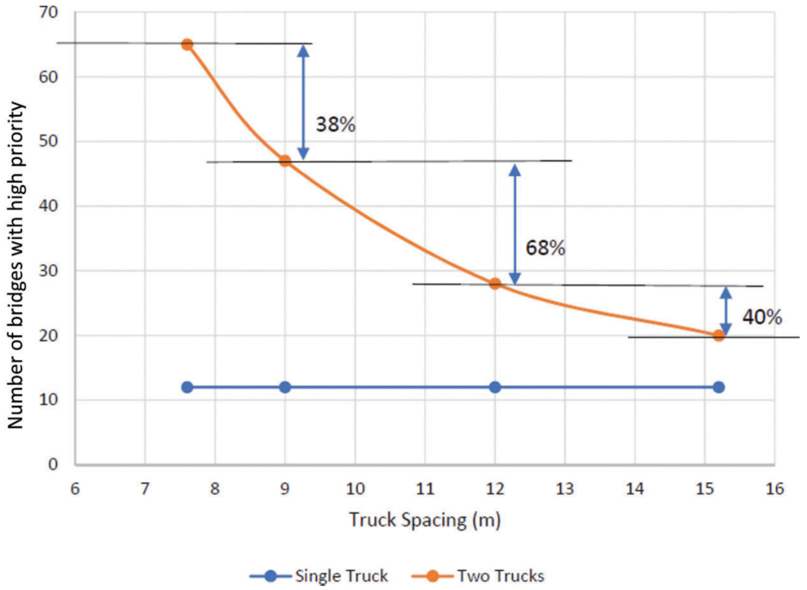


Figure 2.7 Number of high-priority bridges for truck type 3S2 at different truck spacings for a single truck and for a platoon of two trucks (Birgisson et al., 2020; Othman 2021).

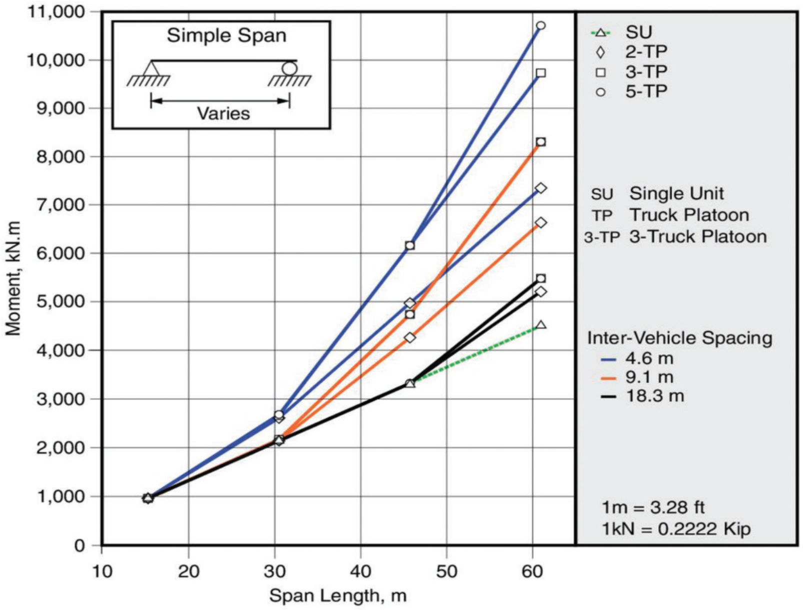


Figure 2.8 Platooning impact on bridge loading (Sayed et al., 2020).

2.4.6 Impact on Pavement Infrastructure Condition/ Longevity

The literature on platooning impact on pavements suggests the following.

- Platooning has been associated with channelized truck loading application because the lateral positions of trucks in a platoon are expected to be similar, as opposed to the scattered lateral position of human-driven trucks (Figure 2.10).
- Platooning will cause shorter time headways between consecutive trucks because of reduced inter-vehicle distance in platoons; this will hinder self-healing of asphalt concrete and consequently reduce pavement life (Gungor & Al-Qadi, 2020).
- Without appropriate lateral control, platooning effect on flexible pavement life could be negative, due to repeated single point load caused by lane centering and lane-keeping (Chen, Song, et al., 2019).
- Between 25% and 45% greater rutting in channelized sections compared to sections where the load is distributed according to a normal distribution.
- Fatigue cracking failures could be accelerated by a factor of three or more by channelizing the traffic.
- With respect to pavement damage, a single pass of a platooning truck that follows a uniform distribution across the travel lane is equivalent (on

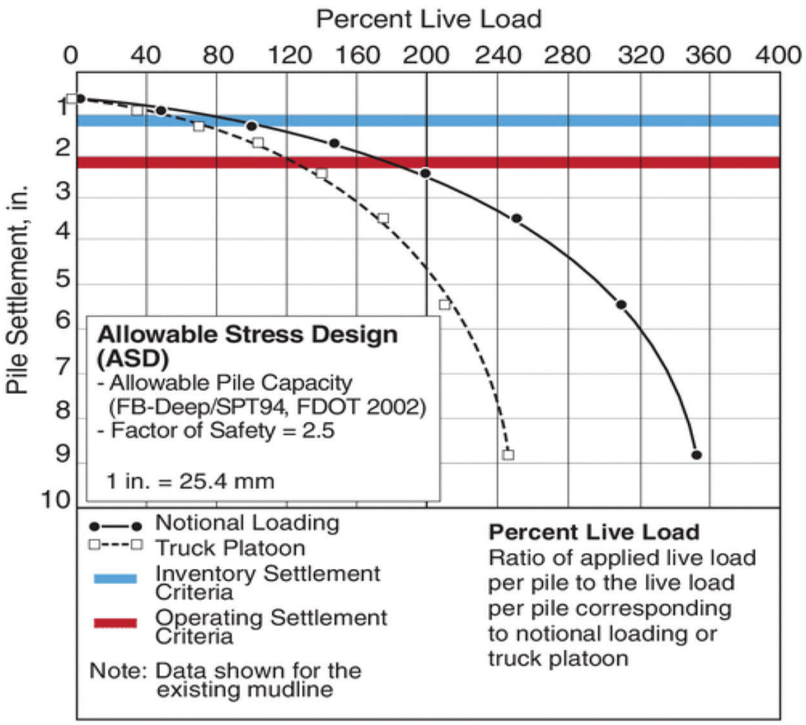


Figure 2.9 Platooning impacts on highway bridge pile settlement (Sayed et al., 2020).

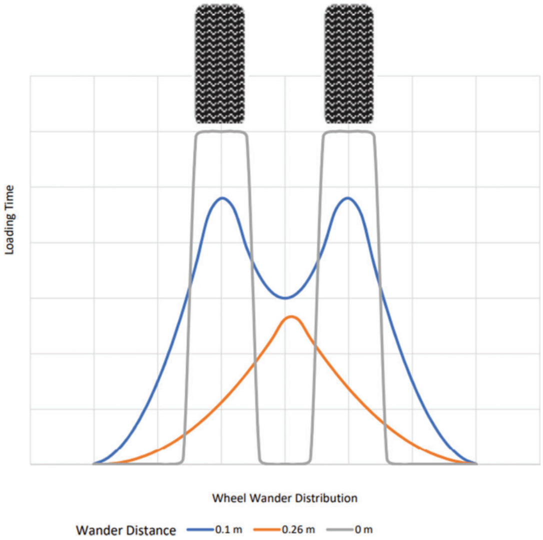


Figure 2.10 Loading time distributions by the level of wheel wander distance.

average) to 0.65 and 0.81 passes of a non-platooning truck.

- Results showed that pavement lifecycle costs could be reduced up to 50% by controlling the lateral position of the platoons for each day.
- With lateral distribution of platooning trucks, pavement longevity is enhanced. Without such distribution, rut depth reaches 15 mm by 1.56 years earlier, and fatigue damage at the bottom of asphalt layer increases by 146% compared to the case for lateral distribution.

Truck platooning is expected to cause channelized truck loading application because the lateral positions of trucks in a platoon are expected to be similar as opposed to scattered lateral position of human-driven trucks. Additionally, the time between two consecutive truck loads will be shorter because of reduced inter-vehicle distance in platoons, which may hinder the self-healing characterization of asphalt concrete and consequently reduce pavement service life (Gungor & Al-Qadi, 2020). The infrastructure challenges caused by truck platooning can be transferred into opportunities by appropriately controlling the lateral position of trucks which could even be highly beneficial to asphalt pavements for wider using of pavement (Chen, Song, et al., 2019; Gungor, 2020). Table 2.5 presents a summary of the literature on the impacts of truck platooning on highway pavement condition/longevity.

2.4.7 Impact on Emissions

2.4.7.1 Information from the literature. Paddeu and Denby (2022) found that there is potentially significant reduction in emissions of similar magnitude (percentage) to that of fuel savings. Fossil fuel combustion also emits CH_4 and N_2O. Stationary combustion of fossil fuels was found to be the third largest source of N_2O emissions in the United States and mobile fossil fuel combustion was the fifth largest source. Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 emissions from natural gas systems, coal mining, and petroleum systems as shown in Figure 2.11 (units in million metric tons of carbon dioxide equivalent).

Advances in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication create opportunities to reduce CO_2 emissions in the transportation sector. Truck platooning is one of the recent technologies that could reduce diesel consumption by heavy-duty vehicles. The formula for converting diesel fuel used to CO_2 emissions is shown on the EPA's "Greenhouse Gas Equivalencies Calculator" website.

$$10{,}180\ \textit{grams of } CO_2/\textit{gallon of diesel} = 10.180 \times 10^{-3}\ \textit{metric tons } CO_2/\textit{gallon of diesel}$$

Therefore, emissions could also be reduced through truck platooning.

2.4.7.2 Case study Indiana—CO_2 emissions reduction at selected corridors in Indiana. Assuming the total diesel saving rate is 4%, which is the conservative estimation (Alam, 2014), and assume the total number of gallons of diesel used in trucks in Indiana is 7E11, the emissions CO_2 can be calculated and plotted as follows.

Assume the proportion of trucks of the overall traffic volume is 22%, and the total mileage of platooning is 20 miles, the energy savings at two locations can be determined. From the results it is obvious that even a small increase in the percentage of trucks engaging in platooning, even when they travel for only 20 miles, yields a large difference in emission reduction.

TABLE 2.5
Impacts of Truck Platooning on Highway Infrastructure Condition/Longevity

Study #	General Findings	Specific Findings	Type of Experiment	Reference
1	Overall negative impact on asset condition	Live loads due to truck platoons would subject the components of the superstructure and foundation to straining actions that are several times higher than their current allowed load rating.	Simulation using analytical methods	Sayed et al., 2020
2	The effect of channelized traffic could result in a faster accumulation of pavement damage	Between 25% and 45% greater rutting in channelized sections as compared to sections in which the heavy-vehicle simulator moved laterally with a normal distribution.	Heavy-vehicle simulator	Harvey et al., 2000
3	The effect of channelized traffic could result in a faster accumulation of pavement damage	Fatigue cracking failures could be accelerated by a factor of three or more by channelizing the traffic.	WesTrack experiment results	Monismith et al., 2000
4	TP could be highly beneficial for pavement infrastructure design with appropriate control	With respect to pavement damage, a single pass of a platooning truck that follows a uniform distribution across the travel lane is equivalent (on average) to 0.65 and 0.81 passes of a nonautonomous truck.	Mechanistic and empirical pavement performance prediction models	Noorvand et al., 2017
5	Centralized control strategy to promote pavement preservation	Results showed that pavement lifecycle costs could be reduced up to 50% by controlling the lateral position of the platoons for each day.	Finite element modeling	Gungor & Al-Qadi, 2020
6	Assess the impacts of different autonomous trucks' lateral control modes on asphalt pavement performance	With lateral distribution of platooning trucks, pavement longevity is enhanced. Without such distribution, rut depth reaches 15 mm by 1.56 years earlier, and fatigue damage at the bottom of asphalt layer increases by 146% compared to the case for lateral distribution.	Finite element modeling	Chen, Song, et al., 2019

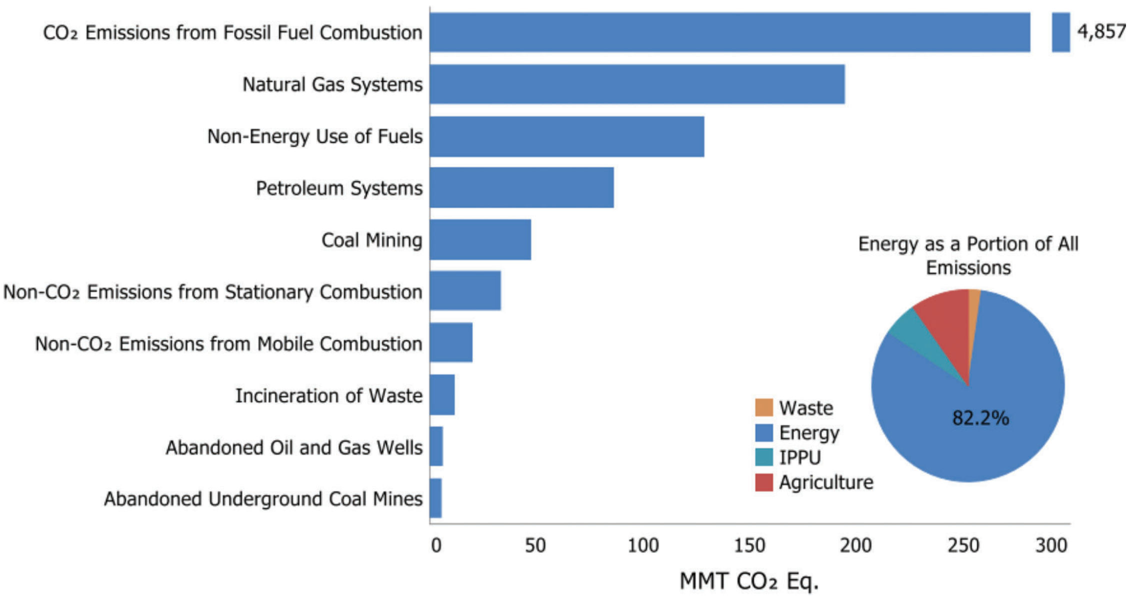


Figure 2.11 Energy chapter greenhouse gas sources (EPA, 2021).

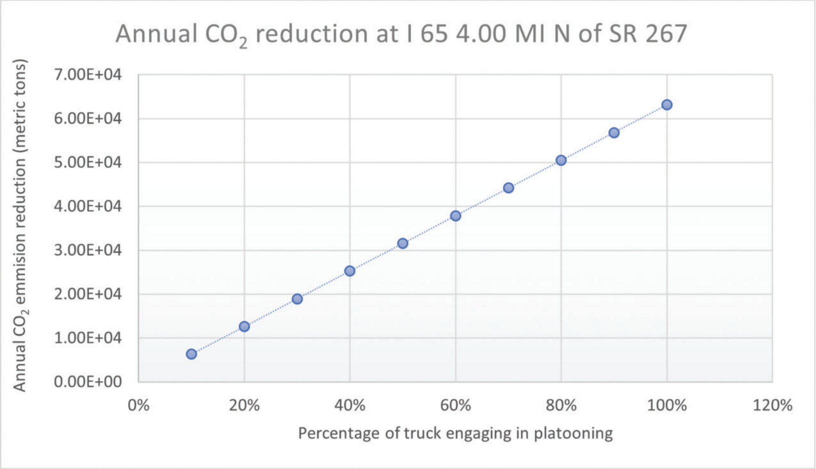


Figure 2.12 Anticipated emissions impacts—truck platooning on a section of Interstate 65.

The energy savings on the I-65 and I-70 sections are presented in Figure 2.12 and 2.13, respectively.

2.4.8 Other Impacts of Truck Platooning

Other impacts include the alleviation of truck driver shortage and exposure to cyber attacks. Truck platooning using electronic concatenation leaves the trucks in the platoon vulnerable to adversarial hacking attacks. If successful, these attacks could lead to not only impairment of travel efficiency, but also to increased crash risk and theft of the cargo. Table 2.6 presents a summary of the literature on the other impacts of truck platooning: truck driver shortage and vulnerability to adversarial hacking attacks.

Given the expected growth in highway freight vehicles over the next few decades, truck platooning is treated as a promising mode of freight transportation in the next decades. Transportation agencies such as INDOT may need to consider appropriate budget allocations and investments to facilitate a safe and efficient environment for all highway users when truck platooning becomes prevalent. Anticipating the transportation impacts of truck platooning and paying attention to segments that will experience sharp growth in truck volumes is beneficial for getting infrastructure well-prepared for this emerging mode of transportation.

The long-term effects of platooning include enhanced safety, fuel savings, and environmental improvement, along with an economic effect. In terms of safety,

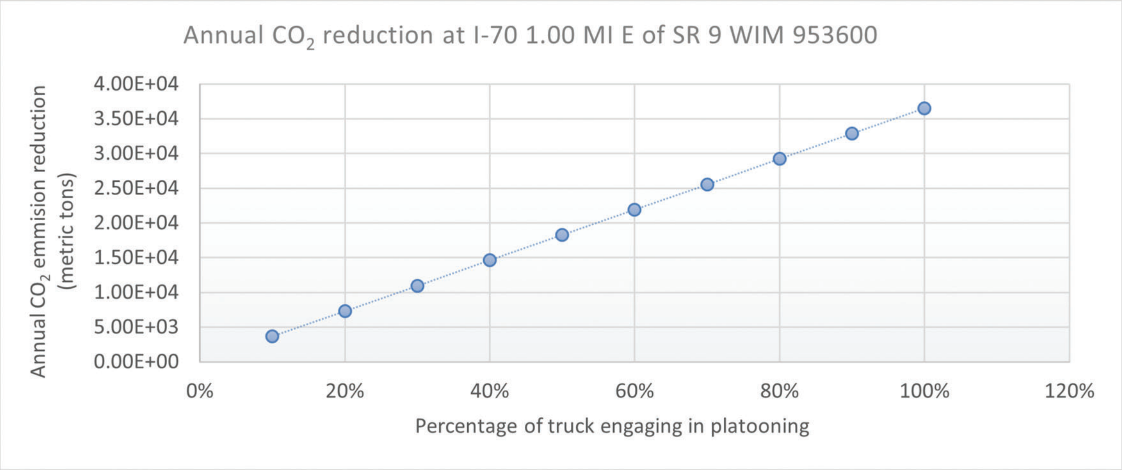


Figure 2.13 Anticipated emissions impacts—truck platooning on a section of Interstate 70.

TABLE 2.6
Other Impacts of Truck Platooning

Study #	General Findings	Specific Findings	Type of Experiment	Reference
1	Alleviate truck driver shortage	Projection: 5 years: shortfall of 500,000 drivers 10 years: shortfall of 1,000,000 drivers	Survey	Bishop et al., 2017 https://favsummit.com/pdfs/richard-bishop.pdf
2	Greater vulnerability to (and consequence of) adversarial hacking attacks	V2V protocol used for platooning are vulnerable to cyber-attacks that could cause serious safety issues (collision) and financial loss (total rerouting of fleets, i.e., theft)	Survey	Ghosal et al., 2021

research has shown that autonomous driving and V2X technology can help vehicles in the platoon avoid traffic accidents by quickly responding to unexpected situations (Woisetschlager, 2016; Yue et al., 2018). In addition the fuel savings is because vehicles travel at short intervals and the air resistance is reduced. (Bujanovic & Yin, 2019; Duret et al., 2020). Finally, it is expected that platooning can shorten the travel time by increasing the road capacity, and the trucks are expected to contribute to the reduction in the labor force by reducing the workload of the truck driver (Guo et al., 2019; Hudson et al., 2019).

2.4.9 The Influence on Truck Platooning-Participation Percentage (TPP)

In the long-term view, it's expected that the TPP of truck platooning will increase gradually. The impacts of platooning are different under different TPPs. From the perspective of network mobility, it is found that the effects of truck platooning may be not significant at low TPP. It is suggested that up to 80% TPP, the difference in network mobility performance is not significant, which suggests that one should not expect a sharp improvement in network mobility after truck platooning becomes mainstream (Lee et al., 2021).

The mobility is gradually improved as the TPP increases. For TPP of 100%, congestion-free conditions were found in the Lee et al. (2021) study to be 10% less severe compared to TPP of 0% (Lee et al., 2021). In terms of safety impacts, the longitudinal safety is improved as the MPR increases, while the lateral safety is reduced. Truck platooning is expected to cause speed differences between lanes, which will impair lateral safety. When truck platooning is enabled for all trucks, the speed difference between lanes is estimated approximately 2.5 times higher than traditional situation (Filho et al., 2022). Therefore, given that highway freight volumes are expected to increase, and that they may be comprised of vehicles forming platoons at different scales of platooning (i.e., TPP), adequate preparation is needed to facilitate the oncoming changes and different strategies should be carried out under different scales of truck platooning.

3. EXISTING MICROSIMULATION MODELS FOR TRUCK PLATOONING EVALUATION

In this chapter, we present a synthesis of existing microsimulation models that have been used in the literature to analyze and evaluate truck platooning in terms of mobility and energy, infrastructure, safety related, network effects, environment, and road user-related outcomes.

3.1 Mobility- and Energy-Related Impacts

3.1.1 The Droege et al. (2021) Study

The researchers analyzed the data from a single truck with a route on hilly terrain and a validated experiment from a two-truck platoon simulation with a framework that studied various control methods for efficient truck platooning on hilly terrain. The control aspects for platooning that were investigated are platoon's shifting transmission algorithm and the lead truck's vehicle control speed.

- For the single truck experiment.
  - Two Peterbilt 579 sleeper cab trucks were utilized for testing, powered by Cummins X15 Efficiency Series engines attached to Cummins-Eaton Endurant 12 speed automated manual transmissions.
  - Each truck was connected to a trailer for a gross vehicle weight of 65,000 lbs.
  - Data were collected from the truck using Peleton's Platoon Pro system, the truck was tested on a closed track.
- For the simulation.
  - Simulink/MATLAB frameworks were created to simulate class 8 single truck and two-truck platoon scenarios with real-world test routes.
  - The lead truck utilized constant set speed cruise control and flexible set speed cruise control.
  - The two trucks also simulated shifting the transmission in different time scenarios.

The result showed that the fuel economy can be improved significantly by (a) adding flexibility to the speed control of the lead truck, (b) providing a look-ahead road grade data to generate an energy-optimal speed profile for the lead truck, and (c) simultaneous shift of each truck's transmission.

3.1.2 The Liu et al. (2020) study

These researchers investigated the cooperative adaptive cruise control (CACC) vehicle string operations by a multi-scenario simulation of a freeway corridor.

- The study carried out the simulation in Aimsum via its microSDK interface. The researchers applied the Aimsun framework to code the study freeway corridor and visualize the simulation experiments.
- The simulation study area is the SR-99 corridor to the south of Sacramento, California. The 13-mi (20 km) corridor starts at the on-ramp of ElkGrove and extends to the off-ramp toward SR-50. It contains 16 on-ramps and 12 off-ramps, as shown in Figure 3.1.
- The study examined the following scenarios of platooning.
  - Cooperative adaptive cruise control (CACC) vehicles are randomly distributed in the system.
  - The vehicles equipped with vehicle awareness devices serve as the leading vehicle of the CACC string.
  - A dedicated lane is adopted for the platooning string such that the CACC string is separated from the regular traffic.
- To model the vehicle operation, the study adopted the models developed by Milanés et al. (2014) to depict the ACC and CACC car-following behaviors.
- The following parameters were used for the analysis.
  - Average travel speed of all vehicles in the studied area.
  - Average fuel consumption of all vehicles in the studied area.
- The fuel consumption results were computed using two models: the VirginiaTech (VT) comprehensive power-based fuel consumption model and the motor vehicle emission simulator (MOVES) model.

3.1.3 The Lee et al. (2021) Study

This study proposed a framework for exploring traffic mobility and safety performance due to the TPP of truck platoons based on microscopic traffic simulations. A platoon formation algorithm was developed and run on the VISSIM platform to simulate automated truck maneuvering. The simulation experiments were conducted using VISSIM. The simulation layout is shown in Figure 3.2.

The study varied the TPP of truck platoons, and the platoon formation algorithm consisted of the truck

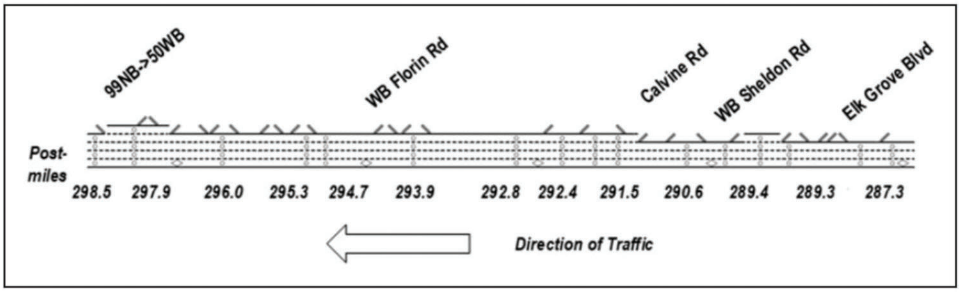


Figure 3.1 Study site: SR-99 freeway, south of Downtown Sacramento, CA.

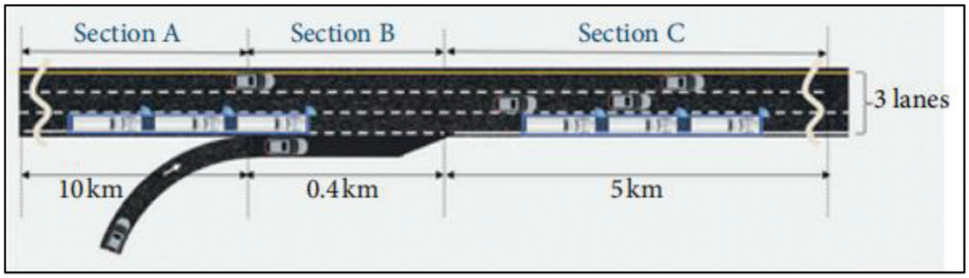


Figure 3.2 Highway section used for the Lee et al. (2021) simulation.

sequencing in the platoon (Part 1), the determination of platoon completion (Part 2), and the speed control algorithm (Part 3).

3.1.4 The Liu et al. (2018) Study

This study extended a state-of-the-art CACC modeling framework to incorporate new algorithms that are essential to describe the interactions among CACC vehicles and manually-driven vehicles in mixed traffic. The simulation platform used was NGSIM. The model was tested in two freeway configurations. The first is a simple 7-km long, 4-lane freeway segment with an on-ramp and an off-ramp. The second network is the 18-kilometer State Route (SR) 99 northbound freeway corridor that contains complex on-ramp, off-ramp, and weaving bottlenecks. For the second scene, real-world data are available to reconstruct the traffic conditions. For the platoon formation, the author adopted the baseline CACC model reported in Milanés et al. (2014), which was developed based on vehicle trajectory data collected during a high-speed car following. The CACC controller had four different driving modes: ACC mode, speed regulation mode, string leader gap regulation mode and string follower gap regulation mode.

3.1.5 The Milanés et al. (2014) Study

These researchers modeled the cooperative and autonomous adaptive cruise control (CACC) dynamic responses in truck platoons using experimental real-world data. They tested a three-truck platoon in collaboration with Volvo trucks. Real-world testing—a modified version of the SAE J1321 Type II fuel consumption test procedure was used to evaluate the fuel-saving benefits of platooning for various aerodynamic tractor-trailer configurations. Three tractor-trailers equipped with CACC control systems, and an unequipped tractor-trailer were used to assess the impacts of platooning on fuel consumption. Auxiliary fuel tanks were installed on the test vehicles to permit direct measurement of fuel use during each test run using a gravimetric fuel-weighing procedure. The platoon specifications were as follows: (a) separation distance/time: 57 ft to 142 ft, equivalent to 0.6 s to 1.5 s at 65 mi/h); (b) truck configuration: standard-trailer vs. aerodynamic-trailer; (c) vehicle speed: 55 mi/h and 65 mi/h; (d) vehicle weight: 31,000 lbs. and 65,000 lbs.

3.1.6 The Taylor et al. (2020) Study

This study used simulation tools to predict benefits associated with Class 8 trucks platooning. The benefits include safety, fuel savings, mobility, and connectivity-enabled control systems framework. The simulation framework consisted of corridor grade data acquisition and post-processing, a single truck simulation (for comparison) using Simulink, and platooning simulation.

The results from the study showed that reducing the aerodynamic drag force can cause platooning Class 8 trucks to save fuel for the lead truck. Following trucks will require less engine power to maintain set speed. For example, two-truck platooning has a fuel savings that is directly correlated to the vehicle speed as aerodynamic drag grows as a function of velocity squared. For 0% road grade, uphill, and downhill scenarios, the fuel savings vary. At 0% grade, 0.703 normalized gallons per-mile when traveling at 24.5 m/s and 1.0 when traveling at 28.6 m/s, a 42% increase two-truck platooning aerodynamic drag force reduce as each truck in a platoon as speed increases, creating a fuel savings. Downhill, two-truck platooning that require engine braking, or coasting, do not yield fuel savings through platooning due to the engine not consuming fuel. Uphill, two-truck platooning fuels savings for grades $<1\%$ uphill on a per mile basis are uniform to 0% grade (flat ground). However, when the uphill grade is high enough to result in an uphill speed decrease, platooning-enabled fuel saving diminishes. For gap control, as unexpected shifts between trucks cause separation additional fuel are consumed to restore the correct gap. In this study based on the real-world routes, truck platooning distance maintenance and gap control is aided by lower vehicle speeds.

3.2 Infrastructure-Related Impacts

3.2.1 The Gungor and Al-Qadi (2020) Study

The researchers carried out centralized optimization of truck platoons to improve roadway infrastructure sustainability. Their study leveraged auto-pilot technologies in connected automated trucks by optimizing the lateral position of each platoon or group of platoons.

The first step was to model the pavement performance, where the authors used advanced 3D pavement finite element (FE) analysis in ABAQUS software, a modified mechanistic-empirical design approach (NCHRP, 2004) to consider the lateral position of trucks and between-vehicle distances. A figure from ABAQUS is shown in Figure 3.3. The second step was to predict the differential damage to pavement in two stages: first, predicting damage from the strains, which transformed into damage, which occurs after N number of load repetitions. The outcome of this step is rutting at the mid-depth of each layer and fatigue damage index for fatigue cracking prediction. As loading input and climate conditions change (e.g., change in modulus because of temperature variation or axle loads), they alter the value of the computed strain which requires this step to be repeated.

The second stage involves combination of differential damages to obtain the accumulated damage. The third step was to model other measures of pavement performance such as rutting in unbound layers, accumulated damage, and deterministic and probabilistic lateral shifting. The fourth step was optimization, where the authors sought to maximize the pavement service life by manipulating the lateral position of truck platoons. They defined the pavement service life as the year when accumulated damage reaches its serviceability limit. To solve the optimization problem, authors introduced a greedy-search solution that yielded the optimal lateral position. The authors then carried out Life Cycle Cost Analysis (LCCA) to quantify the economic impact of the proposed control strategy on pavements, considering agency and user costs.

3.2.2 The Noorvand et al. (2017) Study

The authors of this report assessed the implications of truck positioning on flexible pavement performance and design. The estimated influence of truck load positioning on the long-term performance of transportation infrastructure was estimated by carrying out performance simulations of pavement structures. Scenarios considering both full and partial use by autonomous trucks were considered. They simulated pavement performance using AASHTOWare Pavement Mechanistic–Empirical Design (Pavement ME Design) software (Version 2.2) and modeled load from vehicles in terms of their average annual daily truck traffic (AADT). In all cases, they estimated the pavement performance with respect to rutting, fatigue cracking, and overall pavement smoothness.

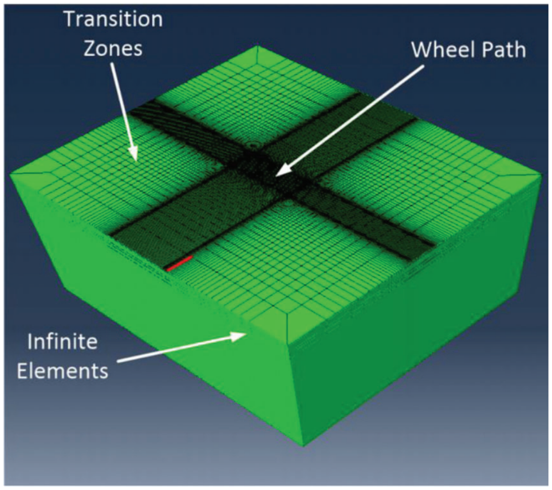


Figure 3.3 A 3D pavement finite element model (Gungor & Al-Qadi, 2020).

3.3 Safety-Related Impacts

3.3.1 The Yang et al. (2019) Study

These researchers analyzed the impacts of large-scale truck platooning on Dutch highways. The work applied microscopic modeling to simulate the impact of truck platooning within critical traffic locations such as merging and diverging areas. First, they built a road network using OpenStreetMap as a background and established the links and connectors of the infrastructure network representing a typical Dutch highway network. Platoons involving two types of vehicles—cars and trucks—were included in the microscopic environment. Longer and heavier vehicle combinations (LZV) were not included in the simulation. They modeled the car-following behavior of drivers using the Wiedemann 99 (W99) model (which is considered more suitable for freeway traffic because of the adaptability of parameters for driving behavior (Arkatkar et al., 2016; Gao, 2008).

To measure traffic flow and efficiency, the road capacity of the entire studied area and travel time at merging area and queue delays were analyzed. To measure safety, traffic safety was translated to the number of stops vehicles need to perform lane changes. The authors cautioned that this kind of behavior normally does not happen in real traffic situations, but it can indicate when vehicles want to perform dangerous maneuvers that can have an impact on the overall traffic management. A variation in speed can affect the overall traffic safety (Michalaki et al., 2016).

3.3.2 The Larson et al. (2019) Study

The authors analyzed a distributed framework for coordinated heavy-duty vehicle platooning using a large-scale simulation of the German Autobahn network (see Figure 3.4). The authors proposed vehicle platoon models, a local controller for platooning coordination and an algorithm to plan paths with minimum fuel cost. The authors analyzed how the total fuel use changes as the number of HDVs in the network increases. They also analyzed the real-world HDV data that show significant platooning opportunities currently exist. The probe data were obtained from HDVs from a single day in a specific region in Europe. To measure the potential for platoon formation, the authors synchronized the probe data to deduce how many vehicles are traveling near other HDVs.

3.4 Economic Efficiency Impacts

3.4.1 The Larsen et al. (2019) Study

The researchers assessed the technical and economic viability of hub-based truck platooning. They investigated different planning and dispatching strategies, from static to dynamic, with respect to profitability and fuel savings across a range of input variables. They concluded that profitability depends on (1) dynamic outlook and (2) whether chauffeurs are allowed to rest while driving in platoons. They proposed a model that describes the schedule-based problem where trucks arrive at random and are dispatched at fixed times. They also presented another model that describes the dynamic version of the problem where trucks are dispatched dynamically and where the planner can look ahead in time. They solved the problem using a discrete event simulator where the set of arriving trucks is enumerated and solved using a greedy insertion heuristic. Their case study was based on data from a transport network model developed for the European Commission. The model covers the entire Europe, and in the development and calibration of the model a wide array of data sets collected from various sources was used. The model includes all modes of freight transportation (road, air, sea, inland waterways) as well as private transport modes. Figure 3.5 shows the distribution of truck destinations in the study area.

3.5 Environment-Related Impacts

3.5.1 The Paddeu and Denby (2022) Study

The researchers assessed the potential of truck automation and platooning in decarbonizing road freight, using a series of scenarios that vary by adoption rates, operational models, and platoon size. They analyzed the factors that either promote or impede truck platooning (Tables 3.1 and 3.2). First, the authors defined a roadmap (2025–2050) with different potential implementation rates of truck platooning in the UK. The roadmap represents a timeframe of a series of possible future scenarios for the adoption of truck platooning. Second, a multi-scenario analysis with the evaluation of polluting emissions and related social costs. Environmental impacts were calculated by considering the emission indicator values of carbon dioxide equivalent (CO_2 eq). In addition to carbon emissions, the authors calculated particulate matter (PM2.5) and oxides of nitrogen (NOx) to carry out a more comprehensive analysis of the impact of truck platooning on air quality. The analysis was carried out considering the Department for Business, Energy and Industrial Strategy's 2018 document and the National Atmospheric Emissions Inventory data sets. In the third step, the authors estimated external costs considering the guidelines provided by Ricardo Energy & Environment (2019) for the UK Department of Environment, Food and Rural Affairs. Three scenarios of truck platooning were analyzed: (a) business as usual, (b) platooned trucks in a mixed-traffic environment, and (c) platooned trucks with exclusive use of the infrastructure.

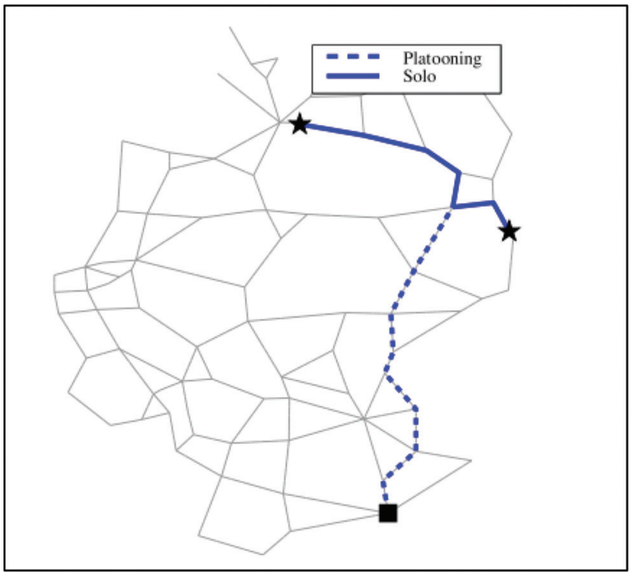


Figure 3.4 Study area of the Larson et al. (2019) study.

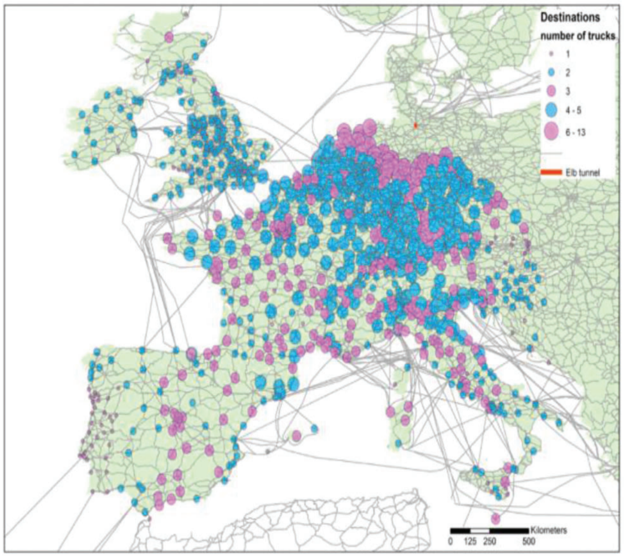


Figure 3.5 Study area of the Larsen et al. (2019) study.

TABLE 3.1
Factors that promote truck platooning implementation

Drivers	Reference
Fuel savings	Janssen et al. (2015), Bakermans (2016), ATA (2020), Aarts & Feddes (2016), Paddeu and Denby (2022), Taylor et al. (2020)
Reduction in emissions	Janssen et al. (2015)
Driver wage reductions/higher productivity	Janssen et al. (2015), Bakermans (2016)
Improved road capacity	Janssen et al. (2015), Bakermans (2016), ATA (2020)
Improved road safety	Janssen et al. (2015), Bakermans (2016), Eckhardt (2016)
Opportunity for new business developments	Janssen et al. (2015)
Use of existing infrastructure	Bakermans (2016)
Barrier	**Reference**
Potential reverse modal shift	Bakermans (2016)
Multi-brand platooning	Janssen et al. (2015), ATA (2015), ACEA (2017)
Cooperation between diverse group of stakeholders needed	Bakermans (2016)
Human machine interface	Friedrichs et al. (2016)
Public reaction	Janssen et al. (2015)
Initial cost of investment in new technology	Janssen et al. (2015)
Distribution of earnings	Janssen et al. (2015), Paddeu and Denby (2022)
Insurance and liability	Janssen et al. (2015)
Regulations and legislations	Janssen et al. (2015), Eckhardt (2016), Paddeu et al. (2019)

3.6 User-Related Impacts of Platooning

3.6.1 The Bishop et al. (2014) Study

These authors reported on the results of testing and evaluation of a driver-assistive truck platooning prototype, for FHWA's Exploratory Advanced Research project titled Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment. They also evaluated the commercial feasibility of driver-assistive truck platooning (DATP). They carried out a survey of fleet managers and owner-operators (who had no driver-assistive truck platooning (DATP) experience at this early stage) regarding their attitude and expectations of DATP. The fleet managers indicated the extent to which DATP would have on their systems: a very positive, somewhat positive, or no impact on driver retention. Also, 39% of fleet managers felt that drivers were very likely, likely, or moderately likely to use a DATP system. For the platoon formation modeling, the authors used actual data of truck movements on a real-world highway section. Promising results were obtained. Platoon participation was 30% to 45%, along 55%–75% of the distance along the 300-mi road segment.

Regarding the user interviews: key trucking company executives were consulted. They indicated that DATP clearly supports operational efficiency. One representative of a large fleet noted, gains in economies of scale that represented a savings in terms of hundreds of millions of gallons of fuel, and that such fuel benefit alone was sufficient motivation to adopt DATP.

For the inter-vehicle aerodynamics modeling, a computational fluid dynamics (CFD) model was used to evaluate the drag reduction of a prototype DATP system. The objectives of the CFD analysis were to optimize the target following distance and to determine the relative drag reduction of the platoon. Fuel consumption tests were carried out, and the Vehicle Dynamics Laboratory team at Auburn University installed a prototype version of Peloton's DATP system on the project tractors and validated proper operation on the NCAT track. Then in August 2015, vehicles and trailers were taken to the Transportation Research Center (TRC) in East Liberty, Ohio, for controlled fuel economy testing. Data collection to test the fuel economy of heavy vehicles was conducted in accordance with the Joint TMC/SAE Fuel Consumption Test Procedure—Type 2 (SAE, 1986). Environmental factors (e.g., wind speed and wind direction), air intake temperature, engine oil temperature, torque request rate, and longitudinal and lateral positioning were analyzed to characterize their influence on fuel savings.

4. PLATOON HEADWAY INSIGHTS USING A DRIVING SIMULATION EXPERIMENT

4.1 Background

The anticipated benefits of connected and/or autonomous truck vehicles (CATs) include reduction of headways between successive vehicles (Figure 8.1), and thus enhancing the overall mobility due to the increased capacity and throughput. On the other hand, headways that are too small can cause discomfort issues for the truck drivers, which can lead to poor user experience. Therefore, it is important to determine appropriate headways that provide a good balance between mobility and user experience in a CATV or CAV (in general) environment.

In the literature, distance headway and time headway are the two common expressions of headway. Distance

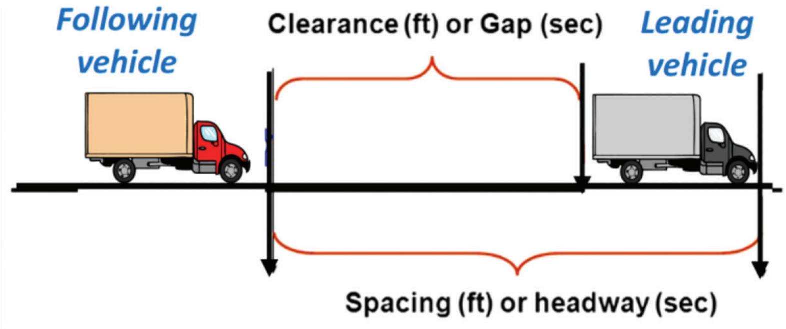


Figure 4.1 Headway between successive vehicles.

headway denotes the bumper-to-bumper distance between the lead vehicle and the following vehicle, while time headway refers to the time interval between two vehicles in car-following scenarios (Fuller, 1981; Winsum et al., 1996). As an important safety indicator, it represents potential danger of a traffic situation, which is commonly used by authorities for the purpose of enforcement (Vogel, 2003). For example, Hong Kong, France, and Netherlands recommend a safe time headway of 2 seconds (Risto & Martens, 2013; Vogel, 2003). As for distance headway, drivers infer distance based on their perception of the physical distance (Cutting & Vishton, 1995). Compared with time headway, it is proposed that driver's judgment in distance headway could be influenced by the variations in vehicle speed and the target physical distance (Risto & Martens, 2013). Also, when the density increases, the safe distance would decrease. Abuelenin and Abul-Magd (2015) proposed that the minimum safety distance headway decreases from 40 to 10 meters, when the density increases from 25 to 40 veh/km.

Also, previous research has indicated the importance regarding human driver's preferred headways for various traffic conditions (Taieb-Maimon & Shinar, 2001; Suzuki & Nakatsuji, 2015). Indeed, drivers' risk perception has influence on their driving behaviors. For example, previous studies revealed that older drivers perceived higher safety risk and tend to keep a longer headway with the vehicle in front (Chen, Sze, et al., 2021; Martchouk et al., 2011; Ni et al., 2010; Shinar et al., 2005). Also, drivers perceive higher rear-end collision risk and report increased discomfort level when the headway gets smaller (Lewis-Evans et al., 2010; Siebert et al., 2014). Lewis-Evans et al. (2010) pointed out that driver's subjective ratings of risk and discomfort level increased significantly when the headways reach a critical value (threshold). Moreover, it is critical to note that there is a gap between the comfortable distance headway and the minimum safe distance headway adopted by drivers (Duan et al., 2013). The authors found that drivers tend to adopt a longer headway when they are instructed to keep a comfortable distance, as compared with the headway when they were instructed to keep a minimal safe distance.

4.2 Experiment Questions and Objectives

A driver's preference in following headway under different driving conditions has been examined to some extent in the literature. However, there is limited research on the difference in driver's comfort level between the following distance decided by human drivers and the following distance decided by the automated driving system. This is an important research question because one can expect that there will be a mix of human drivers and CAVs on the road in the future. Previous studies reveal that drivers tend to deactivate automated driving mode when their perceived trust in such technology is low (Deo & Trivedi, 2019; Hengstler et al., 2016; Molnar et al., 2018; Miller et al., 2016; Petersen et al., 2019). Although the decreased time headway of CAVs would increase the lane capacity and reduce delay, consideration should also be given to the perception of vehicle occupants to guarantee user acceptance. Therefore, it is critical to identify the threshold through the trade-offs between the user-friendly headways (to ensure drivers' comfort level) and smaller headways (to enhance overall mobility) in an automated driving environment. To the best of the authors' knowledge, studies exploring driver's perceived comfortable headways in the context of CAV environment are rare. Compared to the common approaches (e.g., adequate volumes of CAVs running on test tracks or in-service roads), driving simulator experiment is a safe, cost-effective, and flexible approach to assess driver perception and behaviors in a controlled environment (Boyle & Lee, 2010; Chen, Bai, & Sze, 2019; Chen, Sze, & Bai, 2019; Chen, Sze, et al., 2021; Fisher et al., 2011).

This chapter describes a driving simulator experiment that was carried out to acquire insight into platoon headways. This was carried out to ascertain the threshold headways in the context of CAV environment, based on drivers' discomfort levels and their takeover (AV mode to manual mode) intentions. The driving simulator in this study is equipped with level 3 automated driving system (ADS) that is specified in the SAE standard (SAE, 2018). A level 3 ADS feature requires drivers to be vigilant and ready to take over the vehicle under some safety-critical situations. Also, it is of paramount importance that the level 3 ADS-equipped vehicles can adopt proper headways. This is because shorter headway without the careful consideration of driver perception will lead to unnecessary takeovers. Drivers would re-engage in driving tasks as they feel uncomfortable or perceive the close following as an unsafe situation. In addition, the constant stimuli method is also employed to measure the quantitative relationship between the stimulus (different values of distance headway) and driver perception (Gescheider, 1985; Leek, 2001; Simpson, 1988).

The remainder of this chapter is structured as follows. Sections 4.3 and 4.4 provides the details of experimental design, procedures of driving simulator test and the method of analysis. Sections 4.5, 4.6, and 4.7 present the results and discussions, respectively, and finally the findings and future research directions.

4.3 Methods

4.3.1 Participants

Drivers for the driving simulator experiment were required to have a valid full driving license, having driving experience in the United States, and (self-declared) good health condition. Participation in this experiment is voluntary and informed consent was obtained. All participants were conscious prior to the start of experiment since the current study intends to collect the driver's perception during the simulation task. The participants were required to have a good rest on the day before the experiment. Also, they abstained from the consumption of alcohol and caffeinated beverages 24 hours before the experiment. The participants were classified into three categories based on their stated level of caution in driving (i.e., high, medium, and low). Specifically, drivers of Group one stated a high confidence in driving task (i.e., lower level of cautious driving), drivers of group three declared a low confidence in driving task (i.e., higher level of cautious driving), while drivers of Group two reported a middle level. Therefore, group one, two, three drivers were further labeled as "confident," "neutral," and "cautious" drivers.

4.3.2 Apparatus and Driving Scenarios

The driving simulator experiments were conducted on a fix-based device simulator illustrated in Figure 4.2. The simulator was equipped with three full HD LED displays, steering wheel (with force-feedback), pedals (clutch, brake, and accelerator), dashboard (speedometer, control buttons), headlight and turn-signal, mode-shift function (automated or manual mode), and sound system, etc.

SCANeRstudio software was used to generate simulated driving scenarios, where high-resolution images were created to simulate the scenery of road environments in Indiana. One important operational function of the simulator is the transition between autonomous and manual modes. This transition function enables the participant to intervene once he/her feel uncomfortable with the automated driving system. In this study, subjective responses to indicate driver's discomfort levels were measured through a short questionnaire. As depicted in Figure 4.3, a straight road segment in I-465, northern Indianapolis, was adopted as the test section. Two traffic conditions (i.e., high traffic volume and low traffic volume) were simulated to evaluate their impacts on the drivers' perceptions.

4.3.3 Test Procedures

Training Session—A practice run was provided to help the drivers to familiarize themselves with the control of the simulator (particularly, activation of the automated driving mode and the take-over functions) and detect possible syndromes of simulator sickness. Given that the autonomous truck is equipped with the Level 3 automated driving system, drivers were informed of their responsibility to monitor the system performance and to take over if they deemed such action necessary. The instruction to the participants is as follows.

Figure 4.2 Cockpit of the Purdue driving simulator used for the experiment.

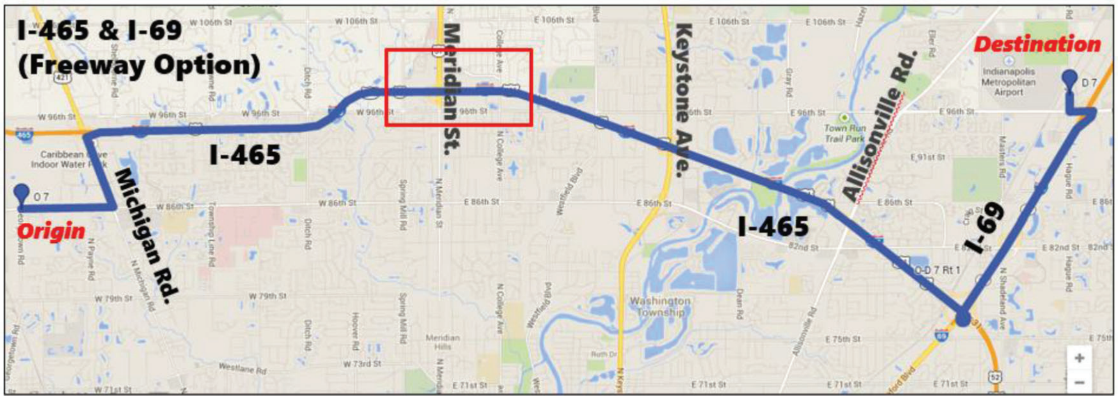


Figure 4.3 Test section for the experiment: I-465 in northern Indianapolis.

> *"Because of the limitations of the enabling technologies that autonomous vehicles rely on, bad weather such as rain, snow, or fog can interfere with the signals from the various sensors. Also, poor lane markings or construction zones can cause the automation to disengage. When the vehicle enters conditions it cannot handle, it will issue a request for the driver to resume vehicle control. The level 3 automated driving system can initiate a take-over request at any time during the drive. It is the responsibility of the driver to remain vigilant of traffic conditions and maintain your ability to resume the driving task when the automation signals that it has reached its limitations. Always remember that you are ultimately responsible for your vehicle and road safety at all times."*

Manual Driving Session—Each participant was then asked to complete ten tests under the manual mode. During each driving test, they were instructed to adjust for a comfortable following distance with a leading vehicle, and to switch the mode from manual driving to automated driving when they considered such "comfortable" level had been reached. The data on the comfortable distance headways indicated by the drivers were collected at the end of each trial.

Automated Driving Session—For the simulated driving tests under the automated driving mode, the vehicle was set to follow the leading vehicle with a predefined headway. Specifically, five distance headways were chosen as the "stimuli" based on the reference values (i.e., the means and standard deviations of the distance headways). For each distance headway, 50 tests were conducted, thus leading to a total of 250 observations. The stimuli presented were randomized and counterbalanced across the participants. At the end of each test, participants were required to answer yes or no for the following two questions.

Q1: Did you experience any discomfort? Y/N

Q2: Did you want to take over the vehicle? Y/N

The second question was asked only if the answer to the first question is, "Yes." In this study, drivers' discomfort levels were collected rather than the comfort levels. Such design was adopted for two reasons. Firstly, our pilot study showed that drivers were more sensitive to discomfort level compared to comfort level. Secondly, one of the benefits of CAVs is that they are expected to have shorter headways compared to the conventional vehicles (human drivers). As we hypothesized that drivers tend to feel more uncomfortable with the decrease in distance headways, it would be more straightforward to measure the discomfort levels.

Three levels of discomfort were further defined: "No discomfort," "Somewhat Uncomfortable," and "Very Uncomfortable." Specifically, if the answer to Q1 is "No," the presented headway would be counted into the "No Discomfort" group. If the answer to the first question is "Yes," then the answer to Q2 was "No," the presented headway would be counted into the "Somewhat Uncomfortable" group. Finally, when the answer to Q2 was "Yes," the presented headway would be categorized into the "Very Uncomfortable" group. Using the schema shown in Figure 4.4, a relationship between the stimulus (distance headways) and driver's discomfort level was attempted in this study.

4.4 Data Analysis

The objective of this experiment was to estimate two thresholds (as shown in Figure 7.4) corresponding to different levels of discomfort. The first threshold is to distinguish the "No Discomfort" headway and the "Somewhat Uncomfortable" headway, while the second threshold is to differentiate the "Somewhat Uncomfortable" and "Very Uncomfortable" headways. This study simultaneously measured the two thresholds by adopting the constant stimuli method (Cantin et al., 2009; Patten et al., 2006). In psychophysical studies, the method of constant stimuli refers to the procedure that determines the sensory threshold by randomly presenting several stimuli. These presented stimuli are expected to be close to the threshold, which is the stimulus value that was detected 50% of the time.

To measure the headway threshold between "No Discomfort" and the "Somewhat Uncomfortable" levels (i.e., *Threshold 2*), all the answers of "Yes" to the first question (*Q1*) were first counted into the "Uncom-

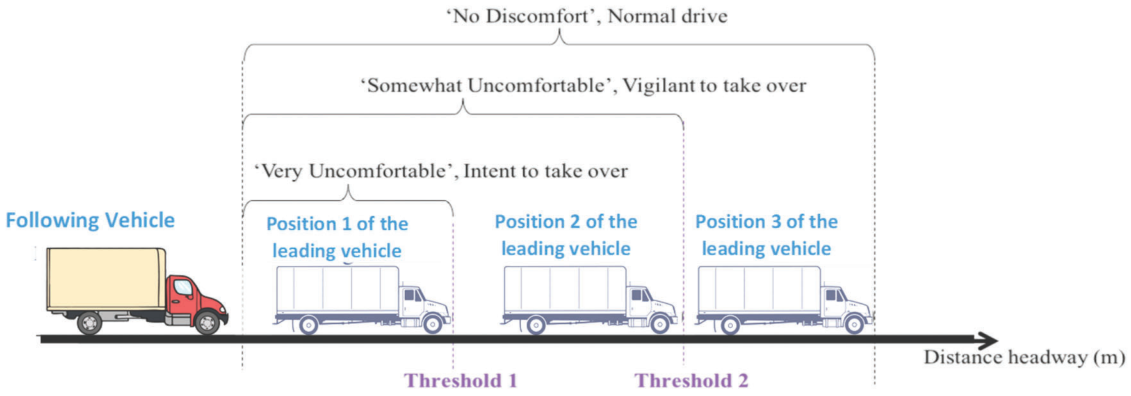


Figure 4.4 Relationship between headways and level of discomfort.

fortable" group. Then, the procedure of conventional constant stimuli method was applied to the two classes—"No Discomfort" and "Uncomfortable." The same procedure was applied to estimate the *Threshold 1*. The proportions of responses for each stimulus value were recorded. Then we fit the data points using the cumulative Gaussian distribution. The two parameters (mean and standard deviation) of the Gaussian distribution were estimated using the maximum likelihood method (probit analysis). The absolute threshold using the mean value of the Gaussian distribution was estimated in this study.

4.5 Results

Different thresholds were estimated for three groups of drivers (i.e., "Confident," "Neutral," and "Cautious"). For the "Confident" driver group, when the distance headway is shorter than the estimated threshold value of 16 meters, drivers tend to take over the automated driving mode. Moreover, the "Confident" drivers in this study tend to feel uncomfortable when the distance headway decreases to less than 22 meters. For the "Neutral" group, drivers tend to feel uncomfortable when the distance headway is shorter than 41 meters and show their intention to take over the automated driving mode when the distance headway further reduces to less than 30 meters. For the last group—"Cautious" drivers, 60.0 meters and 37 meters were estimated for Threshold 1 and Threshold 2, respectively.

4.6 Discussion

The study investigated drivers' comfort-related following distance. The driving simulator in this study was equipped with the level 3 automated driving system. Drivers were required to report their discomfort level and the intention to take over the vehicle during the experiment in order to measure the threshold headways. It is expected that in the future, the safety of road traffic streams dominated by CATs will be improved. Also, the overall mobility will be enhanced owing to the remarkable reduction in headways between the CATs. There exist concerns for the comfort level and trust in AI technologies amongst the drivers and passengers, with the development of CATs. This research provides a significant contribution to furthering the understanding of trade-offs regarding headways between the overall mobility and user experience in an AV environment.

In this study, different headway thresholds were estimated for the three groups of drivers with the control of the same vehicle speed. "Cautious" drivers tend to be more sensitive to the decrease in headways, thus showing intention to deactivate automated driving mode under a longer headway relative to those for the other two groups. In addition, the results revealed that the reference headways measured under the manual driving mode are all slightly longer than the headway *Threshold 2* under the automated driving mode. In other words, this suggests that drivers did not report discomfort even though the CAV keeps a headway shorter than they usually adopt.

These results could be explained by the previous findings that the intention to take over the automated driving mode is associated with the trust in AI technology (Deo & Trivedi, 2019; Hengstler et al., 2016; Miller et al., 2016; Petersen et al., 2019). Molnar et al. (2018) pointed out that the trust in automated driving and the acceptance of technology would influence the decision of transition between automated mode and manual mode. The authors found that one unit increase in trust level is associated with 15% more scenarios in which the driver choose to activate the automated driving mode. Moreover, Du et al. (2020) found that some physiological factors (reflecting drivers' workload and stress) can significantly affect the driver's takeover performance in Level 3 automated driving.

About the effect of driver type, Chen, Sze, et al. (2021) found that older drivers are more cautious and thus tend to adopt longer headway. Comparatively, their mid-aged counterparts are more confident with their driving skills and therefore follow the leading vehicle with shorter headways. Underwood (2013) indicated that novice drivers tend to be cautious followers and maintain a longer headway with the leading vehicle. Despite the effects of driver age and experience, previous studies generally revealed that cautious driving style is correlated with longer headway behavior (Bao et al., 2020; Ivanco, 2017; Saifuzzaman et al., 2015; Shinar & Schechtman, 2002). Consistently, our results suggest that individual driving style would also affect the headway acceptance or comfort level in the context of CAT environment. In particular, the "Cautious," "Neutral," and "Confident" drivers tend to deactivate the automated driving mode when the distance headway reach a threshold of 37 meters, 30 meters, and 16 meters, respectively.

Findings from this research provide useful insights for the autonomous vehicle manufacturers and technology companies regarding the CAT/CAV design that guarantees user acceptance (Vob et al., 2018). For example, personalized autonomous vehicles could be designed by learning from a human driver's perception (e.g., different comfortable headways). Moreover, Martin-Gasulla et al. (2019) pointed out that the less cautious car-following behavior (time headway decrease from 1.8s to 0.6s) of CAVs contributes to a 15% delay reduction. However, the results of this study suggest that capacities and delay should be updated using the "use-friendly" headways in CAVs-operation environment. Therefore, transportation planning involving autonomous mobility could be enhanced in the long run.

4.7 Conclusions

This simulator study measured the threshold headways to identify driver's discomfort and intention to deactivate the automated driving mode for three driver types (i.e., cautious, neutral, and confident). Method of constant stimuli was adopted in this study. The reference headways obtained under the manual driving mode were used as the stimuli under the level 3 automated driving mode. Drivers' responses to the two posed questions of the discomfort level and takeover intention were then collected during the experiments. Results reveal the longer headway thresholds of "Cautious" drivers (i.e., 60 to report discomfort; 37 meters to take over the vehicle) as compared with the "Confident" drivers (i.e., 23 meters to report discomfort; 16 m to take over the vehicle). This could be attributed to the effects of physiological factors, driving style, trust in automated driving, and the acceptance of AI technology. The findings from this research are expected to provide useful insights into the balancing act between the enhanced mobility and poor user experience due to the reduced headways in a CAT/CAV environment.

The findings from this research should be interpreted in the context of the limitations. For example, a driver's judgment in distance headway can be influenced by vehicle speed, traffic volume and road conditions. However, the effects of operational and environmental factor on comfortable following headway were not attempted, given the relatively small sample size. Also, the objective responses to indicate driver's discomfort levels could be collected using the electrocardiogram (ECG) equipment. Moreover, the exposure to the technology could be an important factor affecting the perceived trust in automated driving, while such information was not collected in the current study. The recruited drivers in this study are all college students within the same age group. It is essential that future research should incorporate various samples to better understand how different socio-demographic characteristics are related to the trust in automated driving system. Finally, in the extended study, consideration should also be given to the transition time when determining the headway of CAVs to ensure drivers have enough time to take over the vehicle.

4.8 Summary of the Experiment

The anticipated benefits of connected and autonomous vehicles (CAVs) include reduction of headways between successive vehicles, and thus enhancing the overall mobility due to the increased capacity and throughput. On the other hand, headways that are too small can cause discomfort issues for the truck drivers, which can lead to poor user experience. Therefore, it is of great importance to determine appropriate headways which provide a good balance between mobility and user experience in a CAT environment. In addressing this research question, this study used a driving simulator equipped with a Level-3 automated driving system, to measure the threshold headways through the method of constant stimuli. The participants were divided into three categories (i.e., cautious, neutral, and confident) and 250 driving tests were completed for each driver group. The threshold headways that differentiate driver's discomfort and their intention to re-engage the driving tasks were then estimated through the Probit analysis. The results indicate that 'Cautious' drivers tend to be more sensitive to the decrease in headways, thus showing intention to deactivate automated driving mode under a longer headway relative to those for the other two groups. Results of this study are indicative to the specification of user-friendly headways in CAV designs for the manufacturers and technology companies. Personalized CAV could be developed in the future by learning from human driver's perception. Also, the headway thresholds could be applied to update lane capacities and passenger-car-equivalents in the autonomous mobility era.

5. OPPORTUNITIES AND CHALLENGES TO TRUCK PLATOONING

5.1 Technologies That Will Enable/Promote Truck Platooning

5.1.1 Vehicle Electrification and Driver-Assistive Truck Platooning (DATP)

Vehicle manufacturers such as Volvo, Tesla, BYD, and many others have begun production or are projecting imminent production of fully electric semi-trucks. Electrification of freight trucks can entail immediate torque due to a battery-powered motor instead of an engine, enabling safety features that require fine control. Further, the elimination of vehicular emissions will be a significant benefit to involved stakeholders.

Similarly, driver-assistive truck platooning is an emerging technology that requires attention. DATP is a system wherein multiple trucks exchange data, with one or more trucks following a platoon leader. The vehicles will require sensors (typically radar), vehicle-to-vehicle (V2V) communications (via Dedicated Short-Range Communications protocol), global positioning, actuation, and human-machine interfaces for selecting modes for leading or following (Bishop et al., 2014). The sensors allow the platoons to have enhanced situational awareness, which can help mitigate collision incidents. Further, studies have shown that aerodynamic drafting effects can lead to significant fuel reduction, improving operational efficiency (Brownand et al., 2004; Tsugawa, 2014).

One main concern raised in literature regarding DATP is the feasibility of existing infrastructure for facilitating platooning. Bridgelall et al. states that platoonable miles are limited, which can cause an upper bound in operational benefits (Bridgelall et al., 2020). Therefore, transportation agencies such as INDOT may benefit from an evaluation of DATP-preparedness at its highway sections, which could help in decisions regarding expansion and modification of infrastructure or regulating platooning at specific segments.

Further, providing managed lanes (DATP-exclusive) may increase platoon formation while reducing operational challenges (Bibeka et al., 2021). Doing so could increase platoonable miles significantly without a need for new construction. Finally, it must be noted that making accommodations for DATP fleets could elicit induced demand, further accelerating the increase in freight volume, leading to accelerated infrastructure degradation and reduced life cycle duration.

5.1.2 Smart Freight Information Management

Generally, information and communication technology tools could be leveraged to enhance safe and efficient operations in freight transportation in ways that improve visibility, responsiveness, and performance in supply chains (Coronado Mondragon et al., 2012; Giannopoulos, 2004).

By using ICT logistics operations, a smart freight information management system could be established, which will improve freight transportation by enhancing the exchange of information and real-time status updates regarding different business operations in different modes of transportation (Schumacher et al., 2011). A smart freight information management system can contribute to resource management, ports, and terminals operations management, and tracking and tracing. For transportation resource management, the flow of information used for resource management systems, freight information systems for cargo terminals and integrated route planning systems can be efficiently accessed with online communication. The application of such online communication systems has led to decreased delivery times to the customers and the reduction of errors (Aarts & Feddes, 2016).

For ports and terminals operations management, systems that enable the control of the real-time flow of material through the ports and terminals could be improved to improve the efficiency of ports and terminals by decreasing error rates and increasing loading speed (Hsu et al., 2009). For freight and vehicle tracking and tracing, a smart freight information management system enables the monitoring and control of the location of vehicles and freight in the transportation network. Increasingly, providers of trailer-tracking systems are developing systems compatible with intermodal containers and container chassis. These systems leverage internet-connected GPS and RFID devices to track shipments while they are in transit. In addition, cloud-based data management tools help shipping companies to consolidate and analyze this data, providing them with insights into the shipping process that they can use to improve decision-making. The availability of data can also help shipping customers and carriers to make more proactive decisions.

5.1.3 Driving Algorithms Supported by Artificial Intelligence

Given the rapid advancement of machine learning, and its wide applications in CAV research (Dong et al., 2020), using artificial intelligence (AI) models to improve the performance of freight transportation systems has attracted much attention. Fuel consumption is a major cost in freight transportation and there are a variety of factors that influence fuel consumption: travelling speed, acceleration, road gradient, weather, total weight, driving style of the driver, traffic conditions, and road surface. Bousonville et al. (2019) implemented several machine-learning-based models including K-nearest-neighbors and gradient boost to estimate fuel consumption during freight transportation. The models deliver 50% more accurate estimation of fuel consumption compared to regression models without machine learning. Recognizing that 20% of all energy losses on modern vehicles are due to aerodynamic drag, Jaffar et al. (2020) utilized several supervised machine learning approaches to estimate drag coefficients, which will further assist with fuel estimation. With accurately estimated fuel consumption, carriers will be able to guide the operation of their trucks in a way to minimize fuel consumption.

Besides fuel consumption, operational safety (like collision avoidance) can be ensured by the automated driving functions. An important situation for operational safety is the cut-in maneuvers of passenger cars into the truck platoon. Figure 5.1 shows a cut-in situation, where a passenger car cuts into the truck platooning queue from t_1 to t_2. Cara and Paardekooper (2017) developed a Support Vector Regression algorithm in a direct-recursive hybrid forecast framework, which assists to trucks to predict the longitudinal distance, lateral position, longitudinal speed, and longitudinal acceleration of the passenger cars with such intentions. The results using machine learning models are 40% more accurate compared to traditional regression models. Bouhoute et al. (2020) also trained a gradient booting machine on a large public data set for cut-in maneuver recognition and achieved an F1 score of 98% (Bouhoute et al., 2020).

5.2 The Role of Autonomy and Connectivity in Truck Platooning

Opportunities include (a) the introduction of CATs in freight transportation, which is expected to yield many advantages, (b) addressing the limitations associated with human drivers and reducing operation costs. Currently in the United States, truck drivers are not allowed to work more than 11 hours per day and 60 hours per week. This restriction could be relaxed even with a limited level of automation (e.g., level 4) where the presence of a human driver in the truck is required within a truck. Ideally, under the assumption of full automation, the operation time may be extended to as high as 24 hours, which will significantly improve the efficiency of freight transportation and lower the cost. The operation cost reduction is achieved through truck platooning, which is defined as a convoy of trucks traveling at a close distance.

Improving Efficiency—The enabling communication technologies embedded in CATs may reduce the safe distance between trucks to 10 ft from 200 ft. Reducing congestion and braking/accelerating, as well as improving safety, traffic flow, and fuel efficiency are some of the reported and expected benefits of platooning.

Challenges—First, aging and deteriorating infrastructure are considered one of the main barriers to CAV technologies deployment (RAC, 2017). Given that 20% of roadway miles are in poor or mediocre condition and 9.1% of bridges being structurally deficient or functionally obsolete (ASCE, 2017), accurately predicting transportation infrastructure performance becomes even more important to ensure the presence of functioning and well-maintained infrastructure network for CAT advancement. Second, platooning CATs may lead to channelized traffic which could cause severe damage to the existing pavements. Platooning is characterized by three parameters: spacing between trucks, trucks' speed, and the lateral position of the trucks. These three parameters affect hot-mix asphalt (HMA) deformation, HMA recovery, and healing as well as the rate of damage. This would result in flexible pavement life reduction and an increase in maintenance and rehabilitation costs (Gungor et al., 2020). However, current pavement design guidelines do not consider the aforementioned factors, and a design based on the existing guidelines might underestimate the effects of truck platooning.

The robustness of automation systems is also an important consideration. In truck platooning, safety is a critical consideration. Short inter-vehicle distances are key in truck platooning in view of efficiency and fuel consumption, but this can be challenging for operational and functional safety requirements. Since the driver's view of the following truck is blocked when driving at short following distances, the lateral control of this truck needs to be automated as well.

There are statistics suggesting that approximately 40% of the system failure modes are caused by sensor issues (Google, 2015). To ensure the safety performance of the automated system in truck platooning, robustness of sensor and vehicle-to-vehicle communication should be tested, furthermore, corresponding safety countermeasures should be proposed. International Standards ISO: 26262 provides guidelines to prevent or mitigate hazards that can be caused by hardware or software failures. Van Nunen et al. (2016) identified and simulated different types of critical failure modes in the context of autonomous truck platooning, which include V2V (wireless communication) failure and radar failure.

5.3 The Role of Dedicated Lanes

Past studies analyzed the effect of truck platooning on individual road corridors, or links, on road performance. However, measuring the effects on a network may be more informative compared to

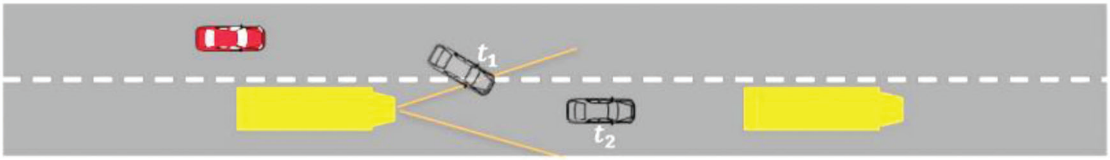


Figure 5.1 Cut-in action by a passenger car between two trucks in a platoon.

measuring the effect of single standalone corridors. Doing this helps capture the holistic effects that characterize a connected road network: implementation of platooning policy at one link affects the route choices of travelers and therefore affects the flow and travel times at not only that link but also at other links. In a hypothetical collection of separate and unconnected corridors (which does not constitute a network), the effect of platoon policy is simply the sum of their individual effects. In this hypothetical scenario, the holistic effect is not applicable. On the other hand, for a connected road network of several corridor links, the effect of the sum of platoon policies at the various links is the outcome, and this is different from the sum of the effects as in the unconnected scenario. This holistic effect is best captured using the traffic assignment (user equilibrium) model formulation.

5.4 Value Engineering of Truck Platooning

5.4.1 Stakeholders and Their Relationships

Truck platooning involves several stakeholders: the autonomous driving (AD) device industry, the Internet of Things (IoT) device industry, and the platoon service platform providers. Chen, Chen, et al. (2021) proposed a simplified business model as shown in Figure 2.15. The arrow signals the direction of cost payment between different stakeholders, which indicates how each stakeholder could benefit while showing how payments made by stakeholders could in turn contribute to the benefit of other stakeholders, creating a balance between costs and benefits. In the model, the platoon leaders are not only the service users, but they also form part of the service providers. To analyze the cost and benefits of platooning, every stakeholder should be considered. If societal benefits are significant, governments will be encouraged to adjust regulation and to facilitate the generation of platoon services and to invest in the development of fundamental infrastructures. In addition, other stakeholders, for example, insurers and customers, who could influence the platoon users should be addressed. In Figure 5.2, COE means Certificate of Entitlement; AD means autonomous driving; IoT means Internet of Things.

Figure 5.2 Simplified representation of new business model for automated platoon vehicles.

5.4.2 Cost of Truck Operations

With regard to platooning trucks, the cost structure would be different compared to that of traditional vehicles. Figure 5.3 shows the cost structure of the conventional vehicle during its lifespan. The car value decreases with year due to the depreciation rate which accounts for 21.5% in year 2017. The result also shows fuel cost accounts for a significant share, up to 68.3%. As for a freight truck, the annual travelling distance is much higher than a private car. Specifically, for platooned trucks, the cost of autonomous driving packages should also be addressed.

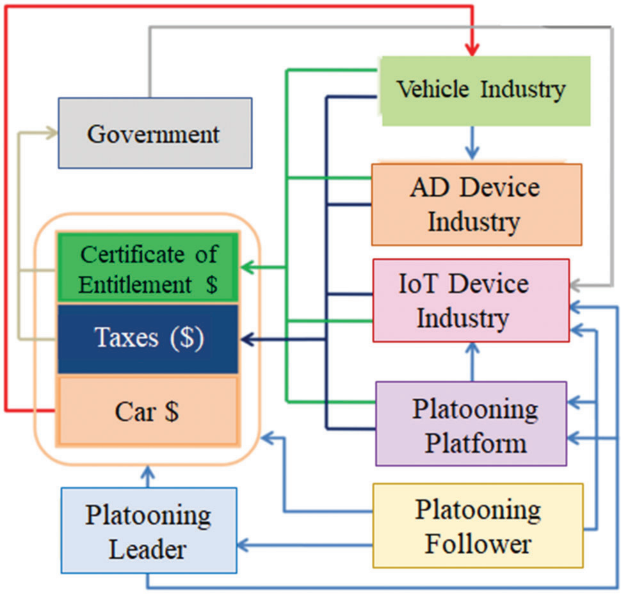


Figure 5.2 Prospective business model for automated platoon vehicles.

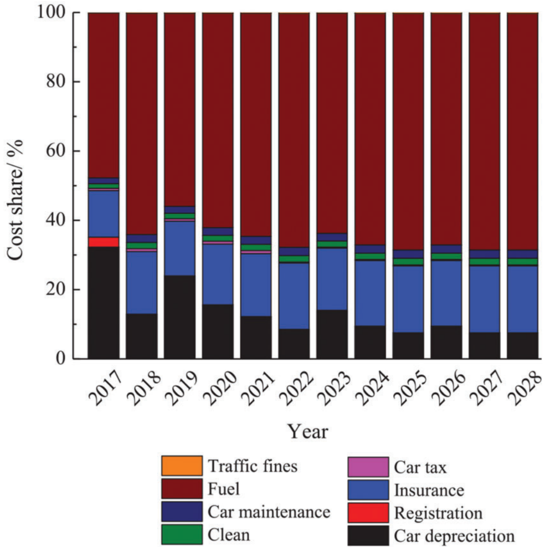


Figure 5.3 Cost structure for a conventional vehicle (Chen, Chen, et al., 2021).

Figure 5.4 presents the cost structure of platoon vehicles in different starting years. As the AD package price decreases significantly with the development of technology, the starting year of the business has a great influence on the cost structure. The AD package accounts for a medium share (23.7% maximum, 8.4% minimum) of cost structure distribution for “business starting year of 2017.” However, the value is the highest in the first year of “business starting year of 2017,” and the value decreases from 23.7% to 1.6% for “business starting year of 2025.” In addition, the fuel cost still

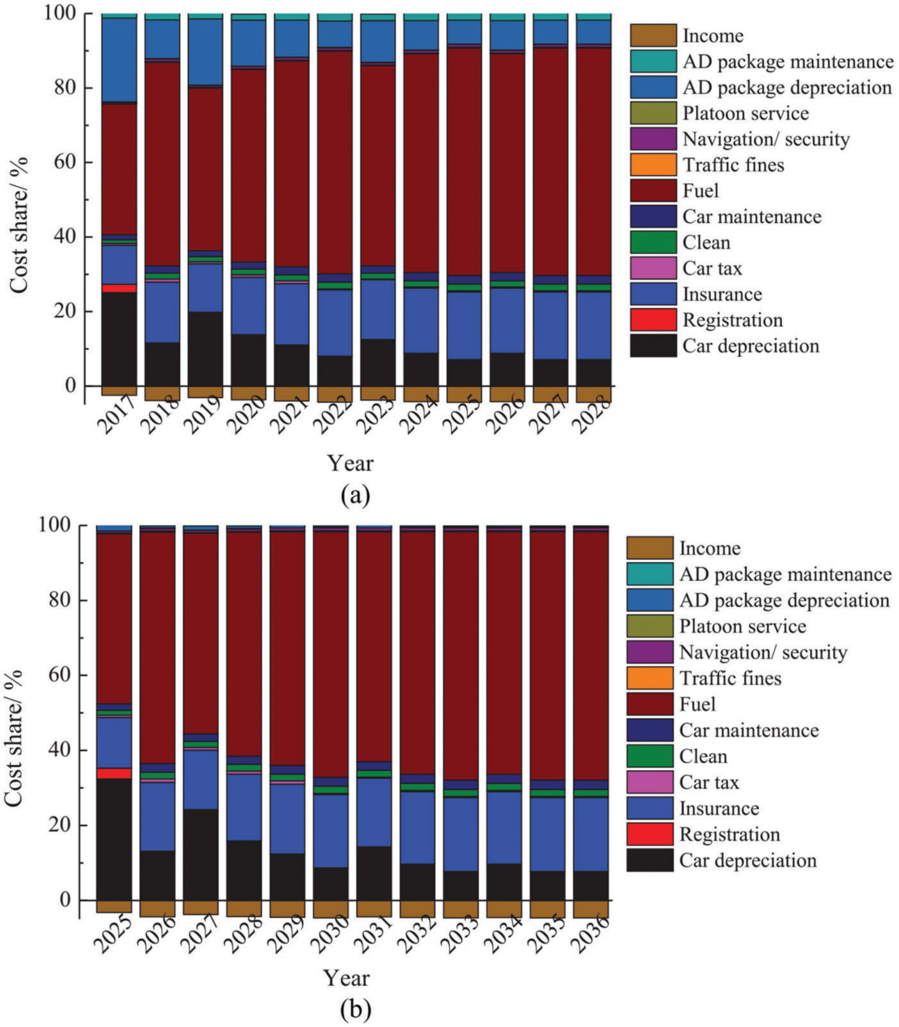


Figure 5.4 Cost structure of platoon trucks: (a) business starting year of 2017 and (b) business starting year of 2025 (Chen, Chen, et al., 2021).

TABLE 5.1
Overview of Platoon Planning Literature

Author	Objective		Constraints			Decisions					Dynamics		
(Year)	Fuel	Delays	Timing	Speed[1]	Detour	Length	PC	R	S	SC	Scheduled	Real-time	Opportunistic
Sokolov et al. (2017)	*		*		*		*	*	*		*		*
Zhang et al. (2017)	*	*	*				*		*		*		
Adler et al. (2016)	*	*	*			*	*					*	
Larson et al. (2016)	*		*		*		*	*	*		*		
Liang et al. (2016)	*		*	*			*			*		*	
Van de Hoef (2016)	*		*	*			*		*	*	*	*	
Nourmohammadzadeh & Hartmann (2016)	*		*				*	*	*		*		
Larsson et al. (2015)	*		*				*	*	*		*		
Liang et al. (2014)	*		*	*			*		*	*	*		*
Liang et al. (2016)	*			*	*		*			*		*	
Larson et al. (2013)	*		*	*			*	*		*	*	*	
Meisen et al. (2008)	*	*	*			*	*				*		

[1] PC = platoon composition, R = route, S = schedule, SC = speed changes 1 = studies without a speed constraint assume a fixed driving speed.

accounts for a significant share of a vehicle which is like the conventional vehicle, although the fuel consumption saving for the platoon leader is assumed to be 5% based on the literature. The insurance cost of the vehicle also accounts for a large percentage, which is like the level of truck depreciation. Due to the high frequency of freight transport, the high insurance cost protects against losses in the event of an accident. Finally, it should be noticed that the cost structure for a platoon leader and a platoon follower are not the same since the leader carries more responsibility of navigating and sensing the surroundings.

5.5 Operational Limitations and Practical Difficulties Associated with Truck Platooning

5.5.1 Platoon Planning and Formation

In cases where there exist an inadequate number of trucks to form a platoon, it is likely that platoons can form spontaneously without planning. However, in the initial stages, when the deployment of platooning technology is not widespread or on routes with little freight traffic, careful centralized planning will be required to assist the formation of platoons (Janssen et al., 2015). A "platooning service provider" (Berger, 2016; Janssen et al., 2015) could bring together trucks from different fleets to form a platoon. Platoons can be scheduled in advance or planned in real-time during execution.

To form a platoon, the departure times, travel speeds and the routes of the trucks in the platoon must be synchronized (Bhoopalam et al., 2018). In this case, complex planning problems may arise in creating platoons, particularly when considering detours. To fully reap the benefits of truck platooning, now and in the future, sophisticated decision support models and tools are required. Such models are not only useful to support platooning operations but can also help quantify the potential benefits of different types of platooning (Bergenhem et al., 2012; Maiti et al., 2017).

Additionally, a platooning service provider can generate different planning strategies based on various objectives and constraints when creating platoons. Two important objectives widely discussed in previous studies are minimizing the system-wide fuel cost and maximizing the number of trucks in a platoon. Table 5.1 summarizes the related pioneering literature in this regard.

6. A FRAMEWORK FOR IDENTIFYING TRUCK-PLATOONABLE SECTIONS ON INDIANA'S HIGHWAY NETWORK

6.1 Prelude

In this report, "platoonability" is defined as the suitability of a highway section for platooning. Although platooning benefits are quantifiable, identifying specific highway segments that are well-suited for platooning is a complex challenge. For efficient platooning, many factors need to be considered in identifying the platooning routes, particularly when two suitable road segments are separated by a road segment that is unsuitable for platooning. In such cases, operational questions arise as to whether the recurring platoon engagement and disengagement are indeed beneficial. Further, a truck platoon needs to travel at a constant high speed for an extended distance and avoid interruptions from interfering vehicles or frequent ramps. Therefore, defining a concrete set of criteria to determine platoonable roads is essential for both convoy route planning as well as for construction scheduling to enable uninterrupted platoonable highway road segments.

In Indiana, trucks carry more than 50% of freight tonnage and constitute 25% of the traffic on interstates. The deployment of truck platooning within interstate highways would yield significant fuel savings but may have a direct impact on flexible pavement performance. The channelization of the platoon and reduced rest time between consecutive loads would accelerate the damage accumulation at the channelized position. Ultimately, this would lead to pavement service life reduction and a subsequent increase in maintenance and rehabilitation costs.

A platoonable section is defined as a section in which trucks must be able to travel in a platoon. Truck platooning is most efficient at speeds higher than 55 mph (Al-Qadi et al., 2021). A platoonable road segment must meet a certain geometry, speed limit, and traffic volume. For efficient platooning, the following is required.

1. Trucks need to travel at a constant high speed for extended distances.
2. The integrity of the platoon should be preserved because interfering vehicles would compromise the platooning benefits and road safety.
3. The geometry of the road must support traveling at a high speed for an extended distance.
4. In addition, the road should allow sufficient speed for efficient platooning and limit traffic to an acceptable volume level.
5. To minimize platooning interruption, exit ramp density to traffic density should be low (Al-Qadi et al., 2021).

Efforts could be made to consider the volume/capacity of a roadway and the expected number of highway exit and entry conflicts. Using these parameters, each roadway section can be assigned a level of segment potential for truck platooning (SPTP), either as a binary variable (yes/no) or a multinary variable that ranges from zero to five—with five being the highest.

6.2 Factors Affecting Platoonability

In this section, we investigate the different factors that affect platoonability. Some of these factors can be placed into two categories: platoon travel speeds and platoon interactions with traffic.

6.2.1 Roadway Functional Class

To harness the benefits of platooning, a truck platoon needs to travel at consistently high speeds for an extended distance. As such, the functional class of a road could provide information regarding its potential for platooning. For example, interstate highways are built to sustain high speeds for extended distances and generally tend to be suitable for platooning. However, there also exist a few expressways that are state roads or US roads.

6.2.2 Ramp Density

Platooning efficiency will be affected largely if there are aggressive cut-ins by passenger cars. These often occur near the highway entry and exit ramps where vehicles need to change lanes. Thus, the density of the ramps for a given segment will affect the platooning efficiency. A policy could be to not have any ramp within the platooning section.

6.2.3 Road Design

The road grade should not be excessive. Platooning at climbing and steep decent sections should be avoided.

6.2.4 Natural Features

Areas of high winds should be avoided, particularly where the wing direction tends to be at an angle to the platooning column.

6.2.5 Pavement Condition

Areas having poor pavement condition should be avoided.

6.2.6 Environmental Conditions

Even at road sections where all other factors are favorable, platooning should not be implemented at times where the road is covered with ice or snow.

6.3 Suitable Highway Segment Candidates for Platooning

Based on some of the above-mentioned factors defined for suitability of platooning, Table 6.1 presents the list of the most favorable potential highway segments for truck platoon operations. A more refined list can be developed after careful consideration of other factors such as pavement conditions, wind speed directions, and so on.

Based on Table 6.1, it is evident that there are several significantly long stretches of the Indiana highways that are suitable for efficient platooning. However, this also points to some operational challenges to platooning in Indiana. This study excludes the length of the under construction I-69 stretch between Evansville and Indianapolis.

TABLE 6.1
Suitable Highway Segment Candidates for Platooning (Examples)

Route Name	Start Point	End Point	Length (approx.)
I-65	138	168	30 miles
I-65	201	253	52 miles
I-65	16	95	79 miles
I-69	19	78	59 miles
I-69	126	157	29 miles
I-74	0	58	58 miles
I-74	113	169	56 miles

Note: For indicated lengths that are punctuated by interchanges, these sections can be broken into smaller segments, with the ramps serving as the approximate start or end points of the proposed

Figure 6.1 Interstate highways in Indiana.

From an operational perspective, one of the largest challenges is the interrupted platooning problem that will persist when adhering to the platoonability performance measures detailed in this report. When truck platoons disengage, theoretically, passenger vehicles should be able to cut-in and perform their normal driving tasks around the trucks. When the truck platoons re-engage after re-entry into platoonable roads, they will need to form the platoons without compromising the safety of the passenger vehicles sharing the same lanes. Therefore, re-engagement of platoons will likely face much heterogeneity in time required to re-engage.

7. MULTI-CRITERIA FRAMEWORK FOR EX ANTE OR EX POSTE EVALUATION OF PLATOONING PROGRAMS

7.1 Introduction

In contrast to decision-support frameworks for platooning system implementation (which is ex ante), this section focuses on after-the-fact. The platooning operations are already taking place, and the agency seeks to assess the efficacy of the initiative. Also, unlike decision-support framework for platooning system implementation (Chapter 6) which focuses on the "inputs," that is, existing conditions), the evaluation framework (current chapter) focuses on the outcomes, that is, safety, mobility, energy use, driver comfort, and so on.

Due to the typically complex and multiplicity of performance criteria typically associated with transportation programs and projects, multi-criteria analysis (MCA) has been identified in the literature as a suitable tool for evaluating transport initiatives. MCA facilitates evaluation of the feasibility of an initiative in terms of multiple performance criteria that often reflect the perspectives of different stakeholders. Chung Li (2022) determined that, to date, MCA techniques have been used broadly (Figure 7.1) and in several areas of transportation (Figure 7.1). MCA techniques have been widely used to evaluate transportation policies (Figure 3.2) in areas such as public transportation (Jain et al., 2014), marine transportation (Gagatsi & Morfoulaki, 2013), infrastructure (Costa, 2001; Rabello Quadros & Nassi, 2015), environmental assessment and sustainability (Baláž et al., 2021; Dubash et al., 2013; Knoll et al., 2016; Salling et al., 2018; Sun et al., 2015; Tzeng et al., 2005), among others. Figure 3.2 also shows other applications of MCA in transportation, such as highway infrastructure development (De Silva & Tatam, 1996; Scannella & Beuthe, 2003; Tabucanon & Lee, 1995), mobility management (Campos et al., 2010; Knoll et al., 2016; Mathey, 2019), maritime transportation (Celik et al., 2009), public transit (Barbosa et al., 2017; Chen, Wang, et al., 2020), technology (Chen, Wang, et al., 2020; Mathey, 2019), logistics (Bulatov, 2021; Labadie & Prodhon, 2014), rail (Macura et al., 2012; Vilke et al., 2020), air (Park et al., 2009), and biking (Barfod, 2012).

In highway infrastructure management, MCA applications include infrastructure planning (Jeon et al., 2010; Salling et al., 2018; Tsigdinos & Vlastos, 2021), design (Brauers et al., 2008; Kuzović et al., 2015; Santos et al., 2019), construction (Ahmadi et al., 2017; Purnus & Bodea, 2016), maintenance (Sayadinia & Beheshtinia, 2020; Suthanaya, 2017) to policy measures design, evaluation, and implementation. It is important to note that a significant fraction of recent MCA transport applications literature focused on sustainable planning and implementation of new technologies such as electric vehicles, autonomous vehicles, and Internet of Things (IoT). To date, there have been no applications in the ex poste evaluation of platooning implementation.

To address this gap, this study proposes a multi-criteria evaluation framework. In this study, the focus is on the various costs and benefits associated with platooning operations. The MCA framework can be used by INDOT to carry out ex poste evaluation of the impacts of platooning at any given section. The proposed MCA framework (Figure 7.3) consists of establishing the decision context, identifying the alternatives to be evaluated, identifying the performance measures, weighting, scaling, amalgamation, and the final assessment. The final assessment could be used for making a judgement on the efficacy of the platooning operations or deciding on whether to continue (or discontinue) the practice. A description of each step is presented in the remaining part of this chapter.

7.2 Elements of the Proposed MCA Framework for Platooning Program Evaluation and Case Study

7.2.1 Establishing the Decision Context

In MCA problems, the first thing needed to be done is to clearly define the context of the analysis. The context

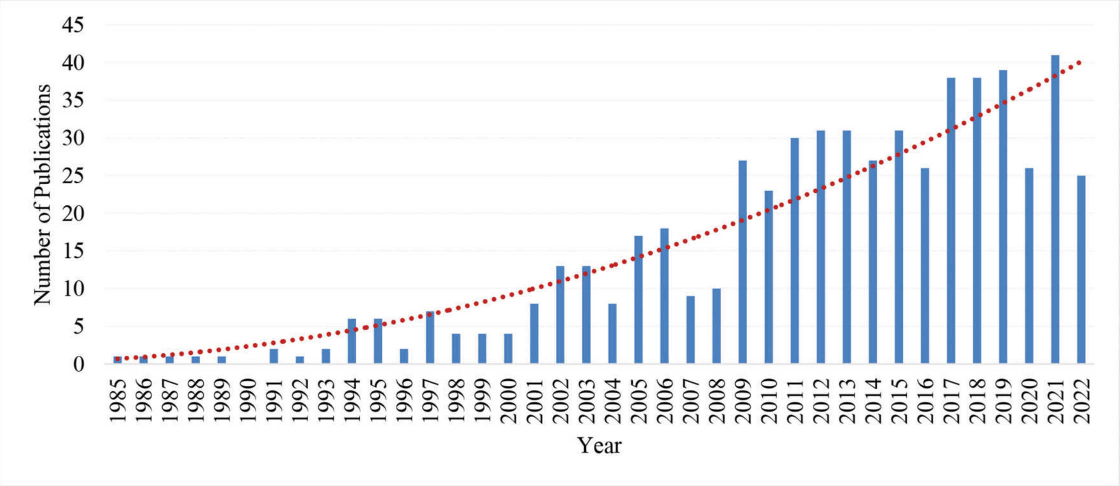


Figure 7.1 Transportation engineering applications of multi-criteria analysis-historical trend (Chung Li, 2022).

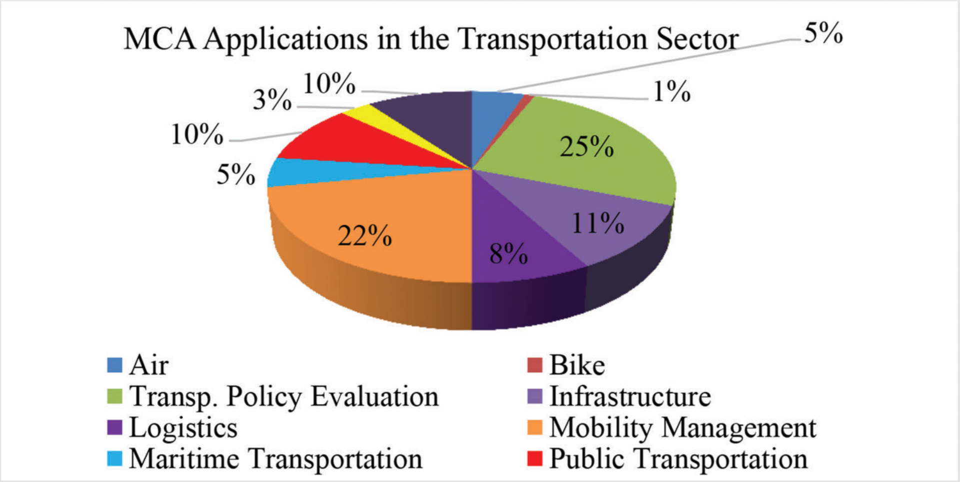


Figure 7.2 Transportation engineering applications of multi-criteria analysis.

accounts for the current situation, goals to be achieved, stakeholders, and key participants or "key players" in the decision-making process. Key players are people who can make a helpful and meaningful contribution to the analysis. Key players can be stakeholders, individuals with an interest or concern in the subject matter or can simply be experts with no investment in the final decision but with knowledge of the subject matter.

In this study, we consider a, 8-mile segment of the Dwight Eisenhower Highway in Indiana, that is, a section of I-70, from State Road 9 Interchange (Milepost 96) to the Mount Comfort Interchange (Milepost 104). This segment is largely a tangent section with a few very gentle curves (Figure 7.4). The proportion of trucks of the total traffic volume is 22%. From the Annual Average Daily Traffic (AADT) data from the online Traffic Count Database System, the AADT is 42,320 vehicles per day. We assume 365 days/year operations of the highway and no work zones.

In analyzing the potential impacts of changes in policies regarding truck platooning operations, two distinct groups of stakeholders are generally involved. On the one hand, there are transportation agencies, responsible for the maintenance and preservation of the highway system, representing the public sector. On the other hand, there are the trucking industry composed of carriers and who seek cost-efficient and effective operations, representing the private sector. Because the highway transportation system is owned and managed by the federal, state, and local transportation agencies, the decision-making falls under the responsibility of these entities. In the context of truck platooning, the goals may include preservation of infrastructure assets, provision of an acceptable level of operational performance in terms of road safety and traffic mobility, and minimization of road user costs.

7.2.2 Identifying the Alternatives to be Evaluated

In an MCA, various possibilities are compared to one another. At least two options are typically evaluated in MCA studies: continuing as at present (that is, the base case scenario) and an alternative scenario (Dodgson et al. 2009). The MCA analyst should be open to possible changes or expansion of the alternatives as the analysis proceeds (Dodgson et al., 2009). Whether an alternative is chosen or not depends on the outcomes/consequences associated with it. For the ex poste evaluation of the impacts of platooning operations in this study, the case study analyzed the following two alternatives:

1. base case scenario: no platooning, and
2. alternative scenario: platooning (100% participation of the trucks).

7.2.3 Identifying the Performance Measures for Comparing Alternatives

The consequences tied to each alternative are those that determine the outcome of the decision-making process. Therefore the consequences play a key role in the MCA (Dodgson et al., 2009). There are several ways that consequences might differ, and those that are important to help attain goals are known as performance measures (Dodgson et al., 2009). Performance measures describe clearly delineated standards by which the various alternatives can be measured and compared (Sinha & Labi, 2007). Performance measures provide an effective basis for informing decision-makers by converting data and statistics into a concise and uniform format. Consequently, in transportation decision-making a broad range of performance measures are established to reflect the concerns and perspectives of all stakeholders for comparing different alternatives and identifying the optimal solution to the problem.

For purposes of transportation decision-making, the selection of performance measures is driven by the goals and objectives of the project, program, or policy. The attributes of a good individual performance measure are appropriateness, measurability, dimension-

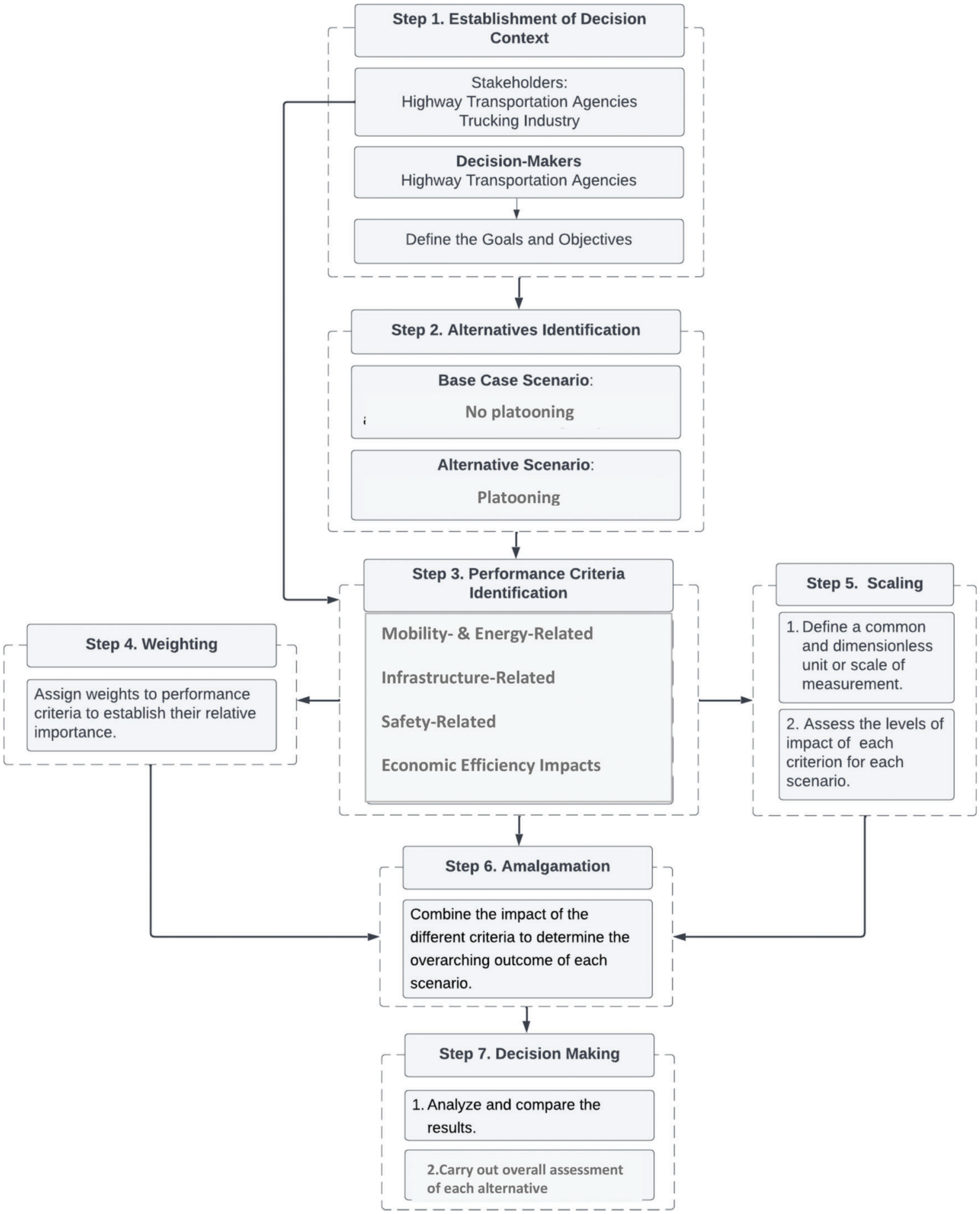


Figure 7.3 MCA framework in the context of truck platooning.

ality, realistic, defensible, and forecastable (Turner et al., 1996). Appropriateness refers to the relevance and adequacy of the performance measure in reflecting at least one goal or objective of the transportation system action. Measurability means that the performance measure can be measured objectively, accurately, and reliably. Dimensionality allows the capture of the level required for each dimension when evaluating a problem and the comparison across different domains (e.g., special and temporal). Realistic facilitates the gathering, generation, and extraction of dependable data related to the performance measure without requiring an excessive amount of work, time, or money. Defensibility relates to the clarity and conciseness of the performance measure to enable the effective communication of the way in which it is interpreted and assessed by decision-makers, stakeholders, and the public. Finally, forecastable means that the performance measure should be

Figure 7.4 Study area showing corridor of interest (dashed green circle).

TABLE 7.1
Performance Measures Used for the Platooning Impact Evaluation in the Case Study of This Report

Goal	Performance Category	Performance Measure
1. Agency cost	Infrastructure damage	Change in infrastructure damage cost (%)
2. Safety	Crashes	Annual crash frequency
3. Mobility	Travel time	Average travel speed (mph)
4. User cost	Energy costs	Fuel use (gallons)

predictable at a future time in a reliable manner using existing forecasting techniques.

Attributes for a good set of performance measures are as follows (Sinha & Labi, 2007). (1) Completeness: the set of performance measures is complete when it can adequately specify to what extent the objective is met. (2) Operational: the set of performance measures needs to be useful and meaningful so that the consequences of the alternatives can be understood while making the problem more manageable. (3) Non-redundancy: the set of performance measures should avoid double counting of consequences. (4) Minimal: the set of performance measures should be as small as possible to reduce dimensionality.

In this study, the performance measures used in the evaluation of the platooning initiative include: infrastructure damage, safety degradation, mobility impairment, platooning truck's vehicle operating cost, and shipping inventory costs were selected for the analysis (Table 7.1). A description of the methodology used for quantifying these performance measures is presented in Table 7.1.

The performance measures include infrastructure damage, safety degradation, and mobility impairment.

Also, vehicle operations cost can be a significant criterion. Platooning operations could lead to significant changes in the vehicle operations costs of shippers and carriers. By allowing smaller headways, the same amount of goods can be transported with in a shorter time, which in turn reduces labor costs, vehicle operational costs (vehicle wear and tear, repair, fuel, etc.), and overhead costs (Adams et al., 2013; Luskin et al., 2000). According to the American Transportation Research Institute (ATRI), the average marginal operational cost per mile of large commercial trucks was reported to be $1.24 in 2020, distributed as follows: fuel consumption cost ($0.31), maintenance and repair cost ($0.15), tire cost ($0.04), and driver's wages and fringes cost ($0.74) (Leslie & Murray, 2021). Since many factors that significantly influence the operational costs of vehicles (e.g., market price of fuel, vehicle fuel-efficiency/consumption rate, vehicle maintenance and repair costs) change over time, values of truck maintenance and repair, tires, and driver's wage and fringe from ATRI's report (Leslie & Murray, 2021) will be updated to the current year using the CPI Inflation Calculator from the U.S. Bureau of Labor Statistics website (U.S. Bureau of Labor Statistics, n.d.) and applied in the present study. However, because fuel prices are incredibly susceptible to any type of disruptions in the demand and supply chain, this study estimates the fuel consumption cost using current fuel prices in the market and the fuel efficiency of semitrailers. Table 7.2 presents the raw values of the platooning evaluation criteria used in this study. Some of these values were calculated using basic traffic and road information at the study corridor. Others were estimated based on the review of the literature (Chapter 2). The safety impact is assumed as the net effect of the change in longitudinal safety (safer) and lateral safety (less safe).

7.2.4 Weighting of the Platooning Performance Measures

One of the key steps in the MCA includes the assignment of weights to the different performance measures to reflect their relative importance from the perspective of the decision-makers. The assignment of weights to the multiple criteria assists decision-makers in evaluating the different transportation alternatives in terms of their performance with respect to the selected criteria for meeting the specified goals and objectives. Moreover, the use of weights facilitates the decision-making process by assisting decision-makers in trade-off analysis, particularly when conflicting measures are considered, to determine the extent to which one performance measure might be exchanged for another (Sinha et al., 2009). Different weighting techniques or even slight changes to the weight distributions can significantly influence the outcome. A description of some common weighting techniques used in the MCA is presented in Sinha and Labi (2007).

To assign weights to the different performance criteria considered in the analysis, the present study reviewed past research in which relative weights for common performance criteria used in transportation decision-making were determined from the agency perspective. For bridge management, Sinha et al. (2009) developed relative weights for multiple criteria using direct-questioning and Analytic Hierarchy Process (AHP) techniques. For highway asset management, Li and Sinha (2004) developed agency perspective relative weights for six overall agency goals in Indiana (infrastructure preservation, safety, mobility, agency costs, user costs, and environment) using the direct-questioning approach. The weights were determined as 0.2259 for infrastructure preservation, 0.2319 for safety, 0.2112 for mobility, 0.1922 for agency costs, 0.1776 for user costs, and 0.1715 for environment. More recently, in the context of truck operations, Yang and Regan (2013) proposed a multi-criteria methodology to prioritize different transportation system alternatives involving trucks operations in California. The authors of that study surveyed public agencies and trucking industry to develop relative weights for the following performance criteria: project cost (0.405), safety hazards (0.2564), traffic congestion (0.1424), air pollution (0.0486), pavement damage (0.0337), productivity (0.0855), and travel time reliability (0.0285). It should be noted from the studies by Li and Sinha (2004), Sinha et al. (2009), and Yang and Regan (2013), that from the agency perspective, the safety and mobility performance criteria are considered top two priorities whereas the performance criteria related to road user cost (trucking productivity and travel time reliability) are considered least important.

Sinha et al. (2009) stated that in the context of highway management, the weighting of performance measures can help agencies to assess the full consequences of competing highway investment practices or policies (in terms of the various costs and benefits accruing to the agency, user, and the community) and thus identify the best alternative. The authors used the

TABLE 7.2
Raw Values of the Platooning Evaluation Criteria Used in This Study

Performance Measure	**No Platooning (Base Case)**	**Platooning Case (Assume 100% TPP)**
Agency cost (infrastructure degradation)	0	35% increase in life cycle costs
Road user cost reduction (fuel savings)	0	16 million gallons saved
Mobility (change in travel time)	0	92% increase in capacity
Safety (overall reduction in crashes)	0	5% net increase in safety

Analytical Hierarchy Process to derive weights across performance criteria for highway asset management. Their findings (Figure 7.5) show that the distribution of weights across various highway performance criteria based on the agency perspective can differ from that based on the road users' perspective.

Table 7.3 presents the average and normalized weights of the platooning evaluation criteria that were then used in this study.

7.2.5 Scaling of the Platooning Performance Measures

Scaling consists of establishing a common and dimensionless unit or scale of measurement that allows all performance measures to be expressed in the same units (e.g., 0 to 100) to enable comparison of the performance measures, making it easier for decision-makers to evaluate and combine various effects to yield the overall desirability of each alternative. Two scenarios can be expected in the evaluation of any project, the certainty scenario, and the risk scenario. When a decision is being made under a certainty scenario, the value function technique is used; however, when a risk scenario is being considered, the utility function approach is used (Sinha & Labi, 2007).

Li and Sinha (2004) developed a methodology for multi-criteria transportation investment decision-making in the state of Indiana. Key aspects of that research effort were to identify the relevant evaluation criteria for asset management, establish the criteria weights and utility functions, and combine weighted and scaled evaluation criteria to yield an overall, amalgamated utility for each candidate intervention. The study showed how such processes were critical for multi-year project selection and trade-off analysis. The case study discussed in this report focuses on how that study established utility and value functions for the evaluation criteria. The utility functions were developed for each of six overall agency goals—system preservation, agency cost, user cost, mobility, safety, and the environment; and also, for each performance criterion under each goal.

In order to develop utility functions corresponding to individual evaluation criteria, an interactive survey was conducted using eighteen randomly selected participants representing the agency and facility users. Using the data obtained, two different approaches were used to develop utility functions—the direct questioning approach and the certainty equivalency approach. The motive for using more than one approach was to ascertain whether results yielded by the two approaches are statistically different. It was seen that at 5% confidence, there was no difference between the two results. Using Ordinary Least Squares and the data collected, single attribute utility functions were developed. These followed any one of the following functional forms ($U(x)$ ranges from 0% to 100%,
$0 < a < 1$):

$U(x) = 1 - e^{-\mathrm{a}(xmax\ -\ x)}$ where $0 < a < 1$, U(x) ranges

$U(x) = 1 - e^{-\mathrm{a}(x)}$

$U(x) = 1 - e^{-\mathrm{a}(x\hat{}2)}$

$U(x) = e^{-\mathrm{a}(x\hat{}2)}$

The developed utility functions for the evaluation criteria are shown in Figure 7.6. The calibrated coefficients are *a* and *b*. *k* values are adjustment factors that ensure that the maximum utility value (of 1.00) is attained when the performance indicator *x* is at its most desirable value.

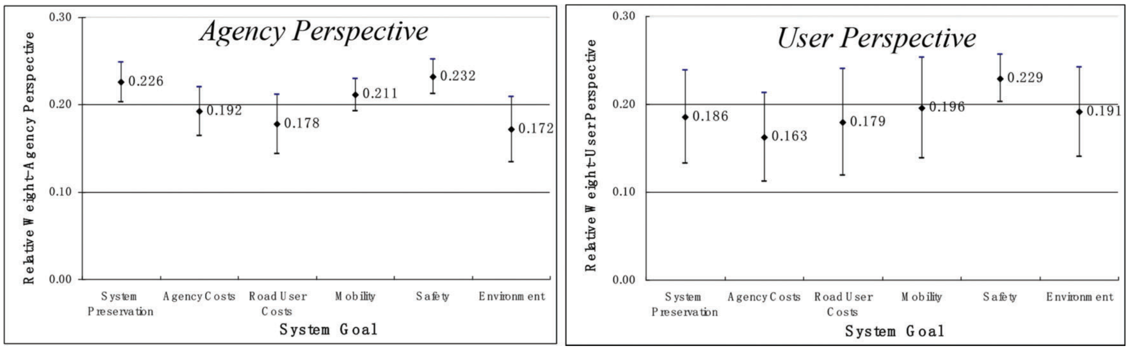


Figure 7.5 Relative weights of highway asset management goals in a previous study in Indiana (Sinha et al., 2009).

TABLE 7.3
Assumed weights of the platooning evaluation criteria used in this study

Performance Measure	Agency-Assigned Weight
Agency (system preservation and other agency costs)	0.125
Road user costs (fuel)	0.213
Mobility	0.261
Safety	0.401
Total	1.000

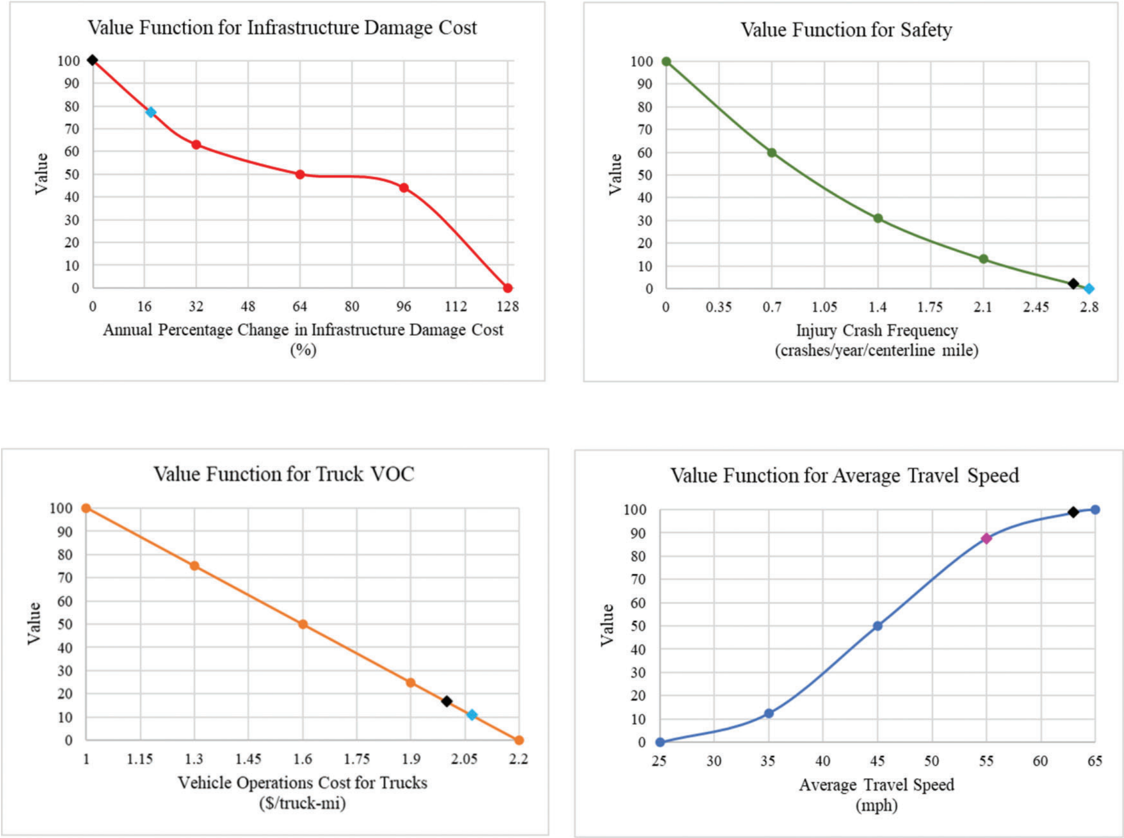


Figure 7.6 Calibrated utility functions (adapted from Chung Li, 2022) used for the platooning decision evaluation of the current study.

7.2.6 Amalgamation of the Weighted and Scaled Performance Measures

After scaling the performance measures to yield common and commensurate units of measurement, the next step is to combine them to determine the overarching outcome of an alternative. This process is known as amalgamation. To do this, several methods could be used: the weighted sum method, benefit/cost ratio method, the goal programming method, and the utility function method. A brief description of these methods is provided next.

7.2.6.1 Weighted Sum Method (WSM). A simple and easy method to combine the scaled performance measures is the weighed sum measure. However, a downside of this method is that it does not take into consideration the inherent preference among the attributes. This method sums up all the individual weighted values to obtain the final value of the utility of an alternative (Equation 7.1):

$$U_i = \sum_{j=1}^{m} w_j s_{ij} \qquad \text{(Eq. 7.1)}$$

Where,
w_j: weight of the performance measure j.
s_{ij}: scaled value of the performance measure j for alternative i.
m: number of performance measures.

It may be noted that the highest value of U_i corresponds to the best choice of that alternative. In addition, the performance measures need to be utility independent and preference independent if preference-based methods are used in the scaling of the values. performance measures are utility independent when each criterion does not depend on the levels of other performance measures. In the case where the trade-offs of two performance measures do not depend on the level of other performance measures, they are preference independent. The relative weights of each performance measures used in (Equation 7.1 can be obtained using a variety of scaling methods such as the observer-derived wights approach, direct weighing method, analytic hierarchy process (AHP) and gamble method.

7.2.6.2 Multiplicate utility function. Amalgamation can also be conducted through the use of multiplicative utility function of an alternative i as defined in (Equation 7.2):

$$U_i \frac{1}{k}([1+kw_1u(x_{i1})] * [1+kw_2u(x_{i2})] * \ldots * [1+kw_mu(x_{im})] - 1) \qquad \text{(Eq. 7.2)}$$

Where, $u(x_{ij})$: utility of alternative i on the jth performance measure.

w_j: relative weight of performance measure j.

m: number of performance measures.

k: scaling constant, defined as (Equation 7.3):

$$1+k=(1+kw_1)*(1+kw_2)*\ldots*(1+kw_m) \quad \text{(Eq. 7.3)}$$

In order to use this utility function, all the performance measures need to be mutually utility independent. The higher the final utility is, the more superior the project alternative.

7.2.6.3 Benefit/cost ratio method. This method consists of determining the benefit/cost ratio between the weighed sum of the performance measures (benefit) and the alternative cost (Equation 7.4). The higher the volume of this ratio, the more superior the alternative.

$$U_i=\frac{\sum_{j=1}^{m} w_j s_{ij}}{C_i} \quad \text{(Eq. 7.4)}$$

Where, U_i: benefit/cost ratio of project i.

n: number of performance measures.

c_i: agency cost of implementing project i.

w_j: weight of performance measure j.

s_{ij}: scaled value of performance measure j for alternative i.

7.2.6.4 Goal programming method. The goal programming function is another amalgamation method that consists of defining goals (target levels) that need to be reached by using the distance from the goals for each alternative, which is given in (Equation 7.5).

$$U_i=\left(\sum_{j=1}^{m}(s_{ij}-M_j)^p\right)^{1/p} \quad \text{(Eq. 7.5)}$$

Where, U_i: sum of the deviation from the goals.

s_{ij}: scaled value of performance measure j for alternative i.

M_j: target value of the jth performance measure.

m: number of performance measures.

To minimize this function, different metric norms can be used. For instance, to determine the type of distance metric that is being measured, the value for the parameter p can be modified. Three commonly used values for parameter p include $p = 1$, $p = 2$, and $p = \infty$ that correspond to the metric norms "city block" distance, "Euclidean" distance, and "Minmax" distance (or infinity norm).

7.2.7 Analysis of Results and Decision Making

In this last step, alternatives are compared by examining the results obtained from the MCA. At this point, the decision-makers can better visualize the potential impacts of the alternative transportation projects in consideration, so the alternative with the highest level of desirability can be chosen. In cases where there is not a truly dominant alternative (one that is better than all others on every criterion) and different transportation alternatives may excel in different Performance measures. The decision-maker can perform a trade-off analysis to determine how much of one criterion can be "exchanged" for a specific level of another.

In the case study, using the weighted sum method, the total amalgamated impact of the platooning option was found to be superior to that of the no-platooning option. As such, for the case study corridor, the hypothetical implementation of the platooning initiative, is found to be superior to doing nothing.

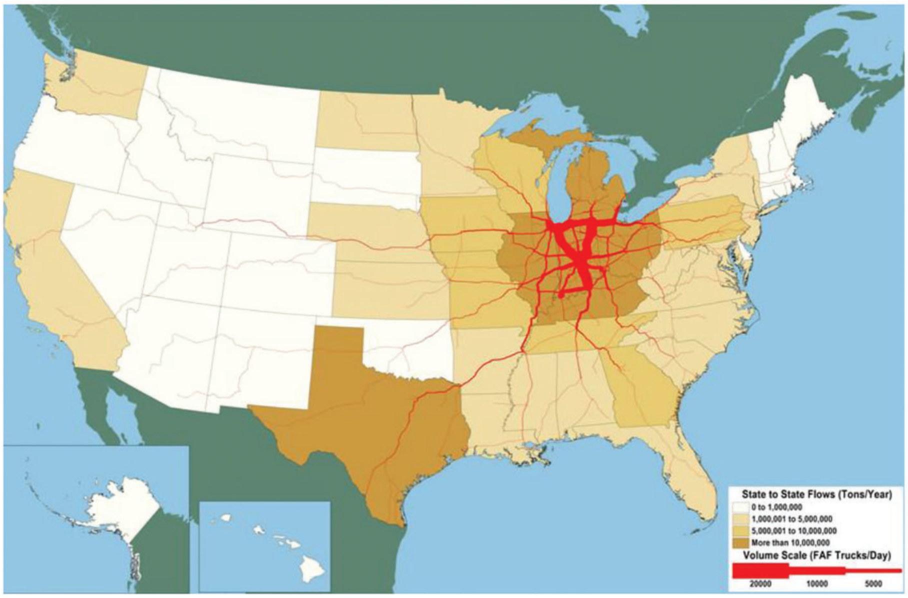
8. FUTURE TRENDS OF FREIGHT TRANSPORTATION IN INDIANA, CHALLENGES, AND OPPORTUNITIES

8.1 Future Trends

Supported by a robust network of interstate highway infrastructure, the United States has seen (and is expected to see) continuous increase in its highway freight dependency over the next few decades. While COVID-19 stalled truck volumes in recent years, projections indicate a swift recovery and continued growth. The American Trucking Association states that "despite significant contractions in 2020 (due to COVID-19), the forecast makes it clear that the long-term trend for trucking, as well as for the overall freight economy is still positive." Projected increases in total freight volume entails revenues rising up to \$1.435 trillion by 2031. Indiana's major interstate highways continues to serve freight vehicles from all other regions of the nation and from Canada and Mexico and is poised to experience significant growth in freight volumes in the next few years and thereafter (Figure 8.1).

For industries in the state whose operations involve significant amounts of shipping, the importance of cost-efficient transportation cannot be overemphasized. Indiana's agricultural and metal industries contribute significantly to the state's GDP. The state is one of the top two leading producers of steel in the country and one of the top five leaders in the production of corn and soybeans. Also, the state is home to several large processing and manufacturing industries that rely heavily on land transportation. Of these industries, those that are related directly to vehicle manufacturing include plants owned by General Motors, Chrysler, Honda, Toyota, Subaru, and Wabash National; industries related to steel work include Nucor, Steel Technologies, Steel Dynamics, AK Steel, US Steel, and ArcelorMittal; and other industries include General Electric, Cummins, Alcoa, and Caterpillar. Also, Indianapolis is a prime center for logistics and distribution facilities; it is home to a FedEx Express hub at the Indianapolis International Airport and distribution centers for companies such as Amazon.com, Foxconn, Finish Line, Inc., Fastenal, Target, and CVS Pharmacy.

(a) Projections of major freight flow by trucks that will pass-through Indiana, 2045



(b) Projections of major freight flow by trucks to, from, and within Indiana, 2045

Figure 8.1 Indiana truck freight projections (Office of Freight Management and Operations, 2017).

A host of major national logistics companies are headquartered or have a hub in Indiana include Celadon, NYK Logistics, MD Logistics, Bunge, Verst Logistics, Langham, CWC Logistics, Aable Trucking & Freight, South Shore Logistics, and Days Warehousing and Distribution. Collectively, these companies serve as the pumps that keep freight flowing on the state's highway network through their distribution, packaging, cross-docking, just-in-time deliveries, warehousing, inventory management, and global freight forwarding. By enabling such transportation services, these freight companies maintain a dynamic supply chain environment that fosters the state's economic vitality and competitiveness (Everett et al., 2014).

Thus, from a general perspective, Indiana's highway transportation system keeps the state's commerce moving. Thanks to the highway transportation network (and other modes that operate in tandem with highways), industries and businesses can efficiently and cost-effectively transport raw materials, commodities, components, and finished products to sites of production, transfer, or processing and to markets located within Indiana and outside the state to serve other states and countries.

Indiana's economic vitality and growth are very strongly linked to the retention and growth of the industries that operate within the state and the attraction of new industries. The government of Indiana continues to provide incentives for business retention and attraction to the state; these initiatives include policies that reduce the cost of operations and enhance business productivity. The exploitation of emerging technologies for highway operations can be considered one such initiative. Technology-based concepts that significantly reduce the overall shipping costs and reduce shipping time, can help reduce the overall operating costs of industries in the state which will ultimately translate into increased productivity and, consequently, increased output, increased employment, higher personal incomes, and expanded tax revenues.

INDOT is responsible for protecting the state's highway infrastructure and to adopt policies that facilitate trucking operations, and to support the state's economic development. As a result, it is increasingly relevant and important to address Indiana's highway asset management and operations associated with the rapidly growing freight volumes and the consideration of emerging technologies. Besides maintenance, increased freight activity necessitates additional enforcement and regulation. While parts of highways in Indiana state a no-truck policy on left-most or two left-most lanes for the safety and efficiency of passenger vehicles, enforcing this policy is more difficult to achieve, and some trucks occupy restricted lanes at times. Projected increases in truck volumes over the next few decades may result in more trucks occupying restricted lanes, resulting in reduced safety, perceived safety, and general efficiency. The primary challenge is to enforce such regulations without reducing highway freight reliability (no late shipments, etc.) while maintaining desired safety and efficiency of all vehicles on the road.

Given expected growth in highway freight vehicles over the next few decades, transportation agencies such as INDOT may need to consider appropriate budget allocations and investments to facilitate a safe and efficient environment for all highway users. Anticipating highway segments that will experience particularly sharp growth in truck volumes and increasing their capacities may be a considerable solution.

Highway freight volumes are expected to increase. Another fundamental development to consider is emerging technologies, specifically, truck electrification and driver-assistive truck platooning (DATP). Vehicle manufacturers such as Volvo, Tesla, BYD, and many others have begun production or are projecting imminent production of fully electric semi-trucks. Electrification of freight trucks can entail immediate torque due to a battery-powered motor instead of an engine, enabling safety features that require fine control. Further, the elimination of vehicular emissions will be a significant benefit to involved stakeholders.

Similarly, driver-assistive truck platooning is an emerging technology that requires attention. DATP is a system wherein multiple trucks exchange data, with one or more trucks following a platoon leader. The vehicles will require sensors (typically radar), vehicle-to-vehicle (V2V) communications (via Dedicated Short-Range Communications protocol), global positioning, actuation, and human-machine interfaces for selecting modes for leading or following (Bishop et al., 2014). The sensors will allow the platoons to have enhanced situational awareness, which can help mitigate collision incidents. Further, studies have shown that aerodynamic drafting effects can lead to significant fuel reduction, improving operational efficiency (Brownand et al., 2004; Tsugawa, 2014).

Therefore, given that highway freight volumes are expected to increase, and that they may be comprised of vehicles forming platoons (with or without electrification), preparation is required to facilitate the oncoming changes. One main concern raised in literature regarding DATP is the feasibility of existing infrastructure for facilitating platooning. Bridgelall et al. (2020) states that platoonable miles are limited, which can cause an upper bound in operational benefits (Bridgelall et al., 2020). Therefore, transportation agencies such as INDOT may benefit from an evaluation of DATP-preparedness at its highway corridors, which could conform decisions regarding expansion and modification of infrastructure or regulating platooning at specific segments.

Further, providing managed lanes (DATP-exclusive) may increase platoon formation while reducing operational challenges (Bibeka et al., 2021). Doing so could increase platoonable miles significantly without the need for new construction.

Finally, it must be noted that making accommodations for DATP fleets could elicit induced demand, further accelerating the increase in freight volume, leading to accelerated infrastructure degradation and reduced life cycle duration.

8.2 Opportunities

8.2.1 Freight Sharing (Freight Consolidation)

According to American Trucking Association (ATA), the trucking industry is short on drivers by an estimated 63,000 positions. And, despite a 15% increase in the median salary for truck drivers over the past six years, the demand for more drivers has not been met (Ben, 2019). With regard to deadhead miles, trucks in the U.S. spend 15%–25% of their miles running empty due to empty backhauls and deadhead miles. Of the remaining 75%–85% non-empty miles, only 64% of available capacity actually gets used—meaning 36% of non-empty miles are underutilized. Freight sharing, the analogue of "right sharing" in freight industry, involves companies sharing space on the same vehicle or container and splitting the fare for their respective portions of the trip. Under such collaborative distribution manner, significant savings over full truckload transportation could be expected (Capstone Logistics, 2016).

There exist opportunities to address these issues. First, to quantify the benefits of freight sharing, significant research has been carried out from technical, sociological, economical perspectives. Islam (2018) develops simulation models for the existing process and the truck-sharing process and validate the results with the real-world data. As per the results, the number of empty-truck trips and the emission can be largely reduced. Also indicating truck-sharing idea boosts port transport capacity, and that it can handle the increasing future truck volume effectively. For more detailed quantification, Liu et al., sought to build models and algorithms to find truck routes with effective freight consolidation (Liu & Zhao, 2019). The results from a mixed integer programming and the real-world data validation indicate it is possible to consolidate and transport electronics cargo with 67% of currently operated trucks, which reduces the operation cost by around 23% and monetary emission cost (MEC) by around 17%.

Second, with regard to the human factors (shipper's willingness and motives) towards the freight sharing system, Islam et al. (2021) conducted both interviews and surveys and identified: five motives (operational efficiency goal, quick transport solution, sustainability policy, convenience-seeking behavior and secure transport process) for truck-sharing, four critical transport attributes (lower charges for freight, distance travelled, full capacity utilization and environmental recognition), four psychological consequences (monetary savings, greater safety, instant availability of trips and clarification of environmental values), and six core values (secure transport process, being careful of money, ease of doing business, sustainability, status in the community and recognition by customers of shippers).

The challenges to freight sharing (Figure 8.2) are associated with the premises for freight sharing, which are the following.

1. The products must be compatible, or handled in the same way (for example, all palletized or all transported via dry van).
2. The products must all fit on the same truck. This can be guaranteed by the existing Less-than-truckload (LTL) shipping manner since the shipments could be organized at the carrier's hub for consolidation.
3. From a geographical standpoint, origins and destinations should be in close proximity of each other; and (d) the delivery schedules should align (Capstone Logistics, 2016).

Other challenges include human factors and constraints (Islam et al., 2019), which can be categorized as follows: constraints pertaining to carriers, shippers, seaports, trucks and miscellaneous. Furthermore, the prominent three constraints are: lack of trust between different collaborators, severity of competition, and lack of coordination. Additional detailed challenges to truck sharing are discussed in Islam and Olsen (2014). Also, a cross-case analysis conducted by Stölzle and Wildhaber (2019) suggests that other factors that influence truck sharing include data security, legal liability,

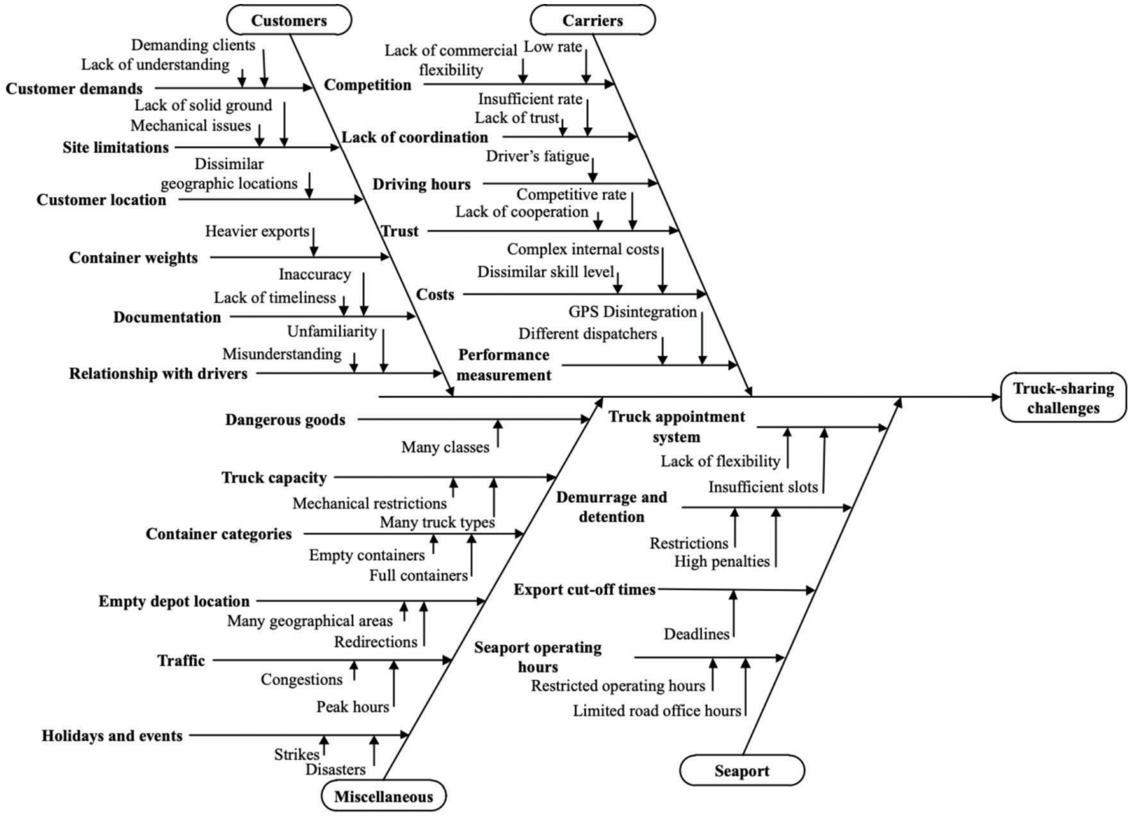


Figure 8.2 A cause-and-effect diagram to demonstrate truck-sharing challenges (Islam et al., 2021).

TABLE 8.1
Comparison of Platooning and Freight Consolidation

		Truck Platooning	Freight Consolidation
Supply	Entity	Trucks	Trucks
	Capacity	Allowed maximum platoon size	Load weight and volume limits
Demand	Entity	Trucks	Load
	Location	Flexible	Fixed
	Service time	Negligible	Loading and unloading time
Benefits	Service quality	Detour, excess travel time, success rate	Detour, safety, reliability
	Individual	Reduced labor and fuel costs	Reduced costs due to economies of scale
	Societal	Reduced emissions, road utilization	Reduced emissions, road utilization

financial contribution system, reputation of the sharing platform, trust and the incentive program are relevant premises for truck sharing in general cargo cooperatives.

8.3 The Sibling Technologies of Platooning and Freight Consolidation

- Freight consolidation combines large freight volumes between terminals through a few links and can enhance shipping efficiency (Campbell, 1990). The concept is similar to passenger ride sharing.
- Multiple trucks that have similar routes and time schedules, and have spare capacity, may collaborate to combine their loads. This requires a mechanism to match trucks with the load they need to pick up and deliver. Hall (1987) provided an overview of different strategies for freight consolidation.
- Freight consolidation, similar to platooning, helps reduce travel costs and vehicle emissions; however, unlike platooning, consolidation involves the transfer of load between trucks which makes it less flexible compared to platooning regarding load compatibility.
- Platoons may be formed by trucks of varying fullness levels and also at any platoonable link in the network while consolidated freight movement occurs only between specific dedicated facilities.
- Compared with freight consolidation, truck platooning requires less coordination between the different parties.
- Min and Cooper (1990) provided an overview of different analytical studies to model and evaluate freight consolidation and describes different solution heuristic and simulation methods used in the various studies. A more recent review with a focus on the routing aspects is provided by Gansterer and Hartl (2017).

Table 8.1 presents a comparison of platooning and freight consolidation.

9. CONCLUDING REMARKS

9.1 Summary and Conclusions

This report begins with an introductory chapter that discusses national trends in trucking and Indiana's contribution to national trucking, and role and responsibility of the Indiana DOT regarding efficient trucking. Then existing truck platooning literature is reviewed, and this covered platoon planning, platforms for platooning impact evaluation, and the various impacts of platooning (energy use, emissions, mobility, safety, truck operators' comfort, infrastructure condition/longevity, and emissions. The review of existing work is further explored with a focus on simulation models that threw more light on how microsimulation was used as a tool to study the impacts of platooning. Then, the report discusses the methods and results of a driving simulation experiment that provided insights on platoon headways.

The report then discussed a few opportunities and challenges to truck platooning, and this served as a basis for subsequent development of a process for identifying truck-platoonable sections, and a multi-criteria framework for ex poste evaluation of platooning implementation at specific corridors. The report then documents the future trends of freight transportation in Indiana and acquires the perspectives of experts and researchers through a questionnaire survey.

The results of the driving simulation indicate the extent to which cautious drivers tend to be more sensitive to the decrease in headways, and suggests that in cases of automated truck driving, choices to deactivate the automated driving mode must be provided under different headways. The driving simulation experiment also provided guidance for truck manufacturers and technology companies, towards the specification of user-friendly headways in automated truck designs. Also, the headway thresholds established in the study could be applied to update lane capacities and passenger-car-equivalents in the era of autonomous trucks.

9.2 Suggested Directions for Future Research

9.2.1 Lane Management and Dedicated Lanes for Platooning

Smaller headways between platooning trucks offer opportunities to increase corridor capacity and reduce freeway congestion and their attendant adverse impacts. Where there exists adequate right of way, new lanes could be constructed for truck platoons at selected segments. However, this can be costly, and instead, the existing lanes could be redistributed/reallocated among automobiles, non-platooning trucks, and platooning trucks. In doing this, however, the road agency must address planning-level questions regarding the platoonability of the highway sections, truck platooning demand, and the outcomes (both beneficial and adverse) of prospective increases in truck platooning participation.

Against this background, future research could identify which links on a given network would be most cost-effective to be subject to lane relocation to accommodate truck platoons. The framework could be similar to those developed or discussed in the literature for other contexts of managed lanes (Adelakum, 2008; FHWA, 2008; Rakha et al., 2010; Seilabi et al., 2020).

9.2.2 Automated and Electric Trucks

It can be argued that land transportation is evolving gradually and inexorably towards the automation of truck operations, specifically, autonomous trucks. However, recent AV-related fatalities on in-service roads have exacerbated public skepticism and eroded some public trust in the safety of AV operations. Further, test tracks for platooning often do not fully mimic real-world driving conditions. As such, most researchers continue to use driving simulation for studying and testing the efficacy of truck platooning. However, as pointed out, in most AV driving simulators, the AV operation is based on commands that are not internal to the vehicle and are rather embedded in the driving environment code (Chen, Leng, & Labi et al., 2020). Researchers will therefore need to develop more robust, representative, and realistic simulations of truck platooning at both microsimulation level and driver cab simulation level. Further, large scale deployment of autonomous trucks must be preceded by approval of regulators and the development of a network of transfer hubs (spots just off the highway where trucks can unload its cargo and refuel before making their return trips) (New York Times, 2022). The New York Times article also identified the advent of electric propulsion of trucks and noted that this will give rise to more questions that will need to be answered, including the locations and mechanisms of recharging. These are worthy subjects of future research, particularly in the context of truck platooning.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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