Human Factors Issues Related to Truck Platooning Operations

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FOREWORD

FHWA is researching the value of the operation of semiautomated and automated truck platoons on public highways to improve and streamline freight operations. An automated truck platoon consists of two or more trucks that use connected and automated vehicle technologies to closely follow each other while maintaining driver safety. The suggested benefits of truck platoons include reduced operating costs for freight companies, reduced environmental impacts through fuel savings and emissions reductions, and improved highway safety and capacity. Efforts to develop and deploy semiautomated trucks are currently underway in the United States and Europe. Proposed sizes range from two to four trucks in a platoon. Despite the very active research and demonstrations of truck platooning operations performed by private entities and government entities including FHWA, a gap remains in research related to the behavior of light-vehicle drivers traveling near truck platoons on the highway.

This report includes a literature review and documents four experiments addressing some critical human factors issues for light-vehicle drivers traveling in the presence of truck platoons. The experiments focus on human factors concerns regarding driver entry and exit of the highway near truck platoons as well as the effect of drivers' knowledge/awareness of platooning operations on driver behavior. This report may be of interest to those who guide operational concepts and who conduct operational environment testing for semiautomated truck platooning during early market deployment.

Carl K. Andersen
Acting Director, Office of Safety and Operations
Research and Development

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Partially automated truck platooning is an emerging technology that allows heavy trucks to follow each other at close distances via automated speed control and direct wireless communications between vehicle systems. This technology, known as cooperative adaptive cruise control (CACC), allows vehicles to detect and respond rapidly to changes in the speed of the vehicle ahead to maintain a set following gap. Automated truck platooning is expected to offer several economic and environmental benefits in a mixed-fleet environment, including improved traffic flow, reduced fuel consumption, and fewer emissions of harmful greenhouse gases. However, how light-vehicle drivers will respond to truck platoons on public roads is unclear. The purpose of the project is to identify, explore, and conduct research related to key anticipated human factors issues that may arise from the operation of partially automated trucks on public highways. First, the research team reviewed existing literature of the state of partially automated truck technology and conducted a predicted operational framework. Next, the team developed a behavioral survey to evaluate driver perceptions of truck operations. The team also conducted a behavioral laboratory experiment to collect driver feedback on novel sign stimuli to communicate platoon activity. The results from these efforts provided critical background information on how drivers perceive, understand, and react to single and grouped trucks on the highway. These findings then supported the development of the first of two driving simulator experiments to explore driver behavior near signed and unsigned partially automated truck platoons at critical highway conflict points. The second experiment was further implemented based on the same roadway scenarios with additional features to evaluate the effects of platoon size and gap distance on behavior and driver perceptions. The results of the experiments can help develop guidance and recommendations for signing and operation of partially automated truck platoons in mixed-fleet environments on public highways.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

ACC	adaptive cruise control
CACC	cooperative adaptive cruise control
CAV	connected and automated vehicle
CMS	changeable message sign
CO_2	carbon dioxide
EU	European Union
FHWA	Federal Highway Administration
GEE	generalized estimating equation
ITS	Intelligent Transportation Systems
NADS	National Advanced Driving Simulator
PATH	Partners for Advanced Transportation Technology
SAE	SAE International
SARTRE	Safe Road Trains for the Environment
SSQ	simulator sickness questionnaire
TACT	Ticketing Aggressive Cars and Trucks
TFHRC	Turner-Fairbank Highway Research Center

CHAPTER 1. INTRODUCTION

Partially automated truck platoons are expected to begin operating on U.S. roadways within the next several years to improve and streamline freight operations. A truck platoon is defined as two or more trucks that use connected and automated vehicle (CAV) technologies, specifically cooperative adaptive cruise control (CACC), to follow each other closely while maintaining safe driving operations. The expected benefits of truck platoons include reduced operating costs for freight companies, reduced environmental impacts through fuel savings and emissions reductions, and improved highway safety and highway capacity (FHWA 2021).

Various levels of automation are being proposed for truck platoons, from SAE Level 1™, where automation controls the truck's throttle and brake while the driver remains in control of steering, through SAE Level 5™, where all driving functions are automated (SAE International 2021). FHWA and Intelligent Transportation Systems (ITS) Joint Program Office have been conducting research to develop and prototype test truck platooning operations (FHWA 2021). Some companies are currently proposing two-truck platooning technologies to freight companies (Commercial Carrier Journal 2023).

Despite the very active research and prototype testing of truck platooning operations, a gap remains in research related to light-vehicle driver behaviors in the presence of truck platoons. For example, would drivers be uncomfortable trying to pass a string of semi- or fully automated trucks? Would a driver's ability to navigate be reduced due to occlusion of roadside signs? How would operating speed, spacing, and the number of trucks in a platoon influence light-vehicle drivers' behavior? These and other behavioral issues need to be explored and addressed to ensure safe and effective operation of truck platoons on the Nation's highways.

In addition to the lack of research into light-vehicle drivers' reactions to platooning operations, no expectations or standardized practices exist for signing, marking, or otherwise making light-vehicle drivers aware of the presence or operation of partially automated truck platoons. This knowledge could be extremely important, especially to drivers who are following but desire to pass a platoon of trucks. For example, a driver currently has no way of knowing that multiple trucks are traveling in a closely spaced platoon. The size of the platoon may also be an important factor in a driver's decisionmaking process; for example, if a driver wishes to take an upcoming exit, knowing the number of trucks in the platoon would help the driver judge whether enough time is available to successfully execute a passing maneuver and take the desired exit at a safe speed. The operation of truck platoons may also negatively impact light-vehicle drivers' ability to enter a highway. A driver trying to merge onto a highway could be faced with a "wall of trucks" and have difficulty finding a suitable gap in which to merge. Truck platoons may also block the view of a driver trying to read exit signs along the highway.

Platoons may pose travel challenges for light vehicles. Undesirable behavior among light vehicles, such as cutting in, might reduce the fuel efficiency of platoons because longer gaps between the trucks create more air drag. Conflicts, collisions, and negative perceptions between heavy trucks and light vehicles are not uncommon. Facilitating awareness of partially automated truck operations among non-truck drivers may help support safe and effective interactions. However, the appropriate amount, content, and delivery method to support positive perceptions and intended behavior of light-vehicle drivers have yet to be investigated. The objective of this task order is to address some of the critical human factors issues influencing light-vehicle drivers and how they travel in the presence of truck platoons.

The research team proposed and completed four research studies in the following order to carry out the task:

1. Light-Vehicle Driver Perceptions of Trucks.
2. Sign Lab Study on Effective Indicators of Partially Automated Truck Platooning.
3. Driving Simulator Study 1—Effects of Truck Platoon Signing on Light-Vehicle Driver Behavior.
4. Driving Simulator Study 2—Effects of Truck Platoon Configuration on Light-Vehicle Driver Behavior.

Chapter 2 describes a summary of findings from the literature review.

Chapter 3 describes the Light-Vehicle Driver Perceptions of Trucks, which was a preliminary study that used a questionnaire to gather light-vehicle drivers' perception and understanding of truck platoons to determine effective language for assessing light-vehicle drivers' comprehension of truck platoons.

Chapter 4 describes the Sign Lab Study on Effective Indicators of Partially Automated Truck Platooning. The study was based on the outcomes from the preliminary study and conducted in the Sign Lab (part of the Human Factors Laboratory at the Turner-Fairbank Highway Research Center (TFHRC) to finalize a set of effective and comprehensible indicators in truck- and road-signing categories.

Chapter 5 describes the Driving Simulator Study 1—Effects of Truck Platoon Signing on Light-Vehicle Driver Behavior, conducted using the University of Iowa's National Advanced Driving Simulator (NADS) quarter-cab miniSim™ in the Human Factors Laboratory at the TFHRC. The study used the results from the sign lab study to investigate whether and how knowledge of truck platooning in the form of signs affects light-vehicle drivers' behavior.

Chapter 6 describes the Driving Simulator Study 2—Effects of Truck Platoon Configuration on Light Vehicle Driver Behavior. The study complemented the first simulator study and evaluated whether and how different characteristics of truck platooning affect light-vehicle drivers' behavior.

Chapter 7 summarizes the key findings and presents conclusions.

CHAPTER 2. LITERATURE REVIEW

This chapter presents a summary of the literature review for the project titled Human Factors Issues related to Truck Platooning Operations. The goal of this review is to assess the current state of knowledge within the field of human factors relative to driver behaviors in the presence of truck platoons.

CURRENT TRUCK PLATOONING OPERATIONS

The number of ongoing truck platoon deployments is small at the time of this review. Several notable pilot fleets have been deployed in Europe via the Safe Road Trains for the Environment (SARTRE) project, the European Union (EU) Truck Platooning Challenge, and KONVOI project (Robinson, Chan, and Coelingh 2010; Janssen, Zwijnenberg, Blankers, and De Kruijff 2015; Deutschle et al. 2010).[1] In the United States, the Partners for Advanced Transportation Technology (PATH) program in California has been one of the major contributors to truck platooning technology and research since 2003 (PATH n.d.).

Several large manufacturing companies are actively pursuing and deploying truck platoon fleets, although efforts have yet to advance past the demonstration stage at the time of this writing (ZumMallen 2017; Heavy Duty Trucking 2017). Other automotive companies have promoted, partnered with, supported, or funded various platooning endeavors (Kroeber-Riel and Hiermeyer 2017). Table 1 provides a summary of major platooning projects. The project principal investigators selected the parameters for their potential effects on light-vehicle drivers' behavior; these parameters will be discussed in more detail in following sections. Brief overviews of prominent truck platooning projects can also be found in Bergenhem et al. (2012); Bishop et al. (2015); and Tsugawa et al. (2016).

As illustrated in Table 1, operational characteristics across platoon demonstrations have varied in several key aspects, including maximum speed, minimum achievable gap distance, level of automation, and platoon length. To date, the minimum safely maintained distance in test deployments is 0.5 s for constant time-gap platoons traveling at 43 mph (70 km/h) or 50 mph (80 km/h) and 10–13 ft (3–4 m) for constant distance-gap platoons traveling at 55 mph (89 km/h). Platoon length is often limited to two or three combination vehicles, although the KONVOI project successfully demonstrated a platoon composed of four identical trucks. Most recently, a brief on-road demonstration led by the FHWA featured a platoon of three heavy-duty trucks traveling on I–66 in Virginia. Three trucks maintained a 0.6 s following gap via CACC tethering while driving at a maximum speed of 55 mph (89 km/h) (Reiskin 2017). Controlled cut-ins by a passenger vehicle demonstrated the ability of a trailing platoon truck to automatically decelerate to achieve the set time-gap distance behind the cut-in vehicle; once the passenger vehicle exited the travel lane, the trailing truck automatically accelerated to resume following the truck ahead at the set time gap.

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[1] KONVOI is the project name and the word for convoy in the German language.

Table 1. Summary of major projects testing physical truck platoons.

Organization/ Project Name	Region	Gap Type	Max. Speed	Min. Gap	Max. Platoon Size	Deployment Type	Following Vehicle Automation	Years Active	References
PATH	USA	Time or distance	55 mph (89 km/h)	10–13 ft (3–4 m) or 0.6 s	3	On-road demo (12 mi)	Speed Steering	1986–present†	Shladover et al. 2005
KONVOI	Europe	Distance	50 mph (80 km/h)	33 ft (10 m)	4	On-road demo (9 d, 3,000+ mi)	Speed Steering	2005–2009	Deutschle et al. 2010; Lank, Haberstroh, and Wille 2011
Energy ITS	USA, Japan	Distance	50 mph (80 km/h)	13 ft (4.7 m)	4*	Test track	Speed Steering	2008–2012	Tsugawa 2013; Tsugawa, Kato, and Aoki 2011
SARTRE	Europe	Distance	55 mph (89 km/h)	19.7 ft (6 m)	4**	On-road demo	Speed Steering	2009–2012	Larburu, Sanchez, and Rodriguez 2010; Robinson, Chan, and Coelingh 2010
Scania	Europe	Time	43 mph (70 km/h)	0.5 s 98 ft (30 m)	2	Test track experiment	Speed	2011–2014	Alam, Gattami, Johansson, and Tomlin 2014
Highway Pilot Connect	Europe	Distance	50 mph (80 km/h)	49 ft (15 m)	3	Limited on-road deployment	Speed Steering	2014–present	Brünglinghaus 2016
Peloton	USA	Distance	55 mph (89 km/h)	40–50 ft (12–15 m)	2	On-road pilot (15,000+ mi)	Speed	2015–present	Lammert et al. 2014
EU Truck Platooning Challenge	Europe	Time	50 mph (80 km/h)	0.5 s	3	On-road experiments	Speed	2016–present	Janssen et al. 2015
US DOT, FHWA, and FMCSA	USA	Time	55 mph (89 km/h)	0.6 s	3	On-road demo	Speed	2017–present	Reiskin 2017

†Truck platoon development began in 2003.

*Three heavy trucks, one light truck.

**One lead truck, three following cars.

FMCSA = Federal Motor Carrier Safety Administration; ITS = Intelligent Transportation Systems; USDOT = U.S. Department of Transportation.

Several platoon pilots have employed synchronization of both longitudinal and lateral movement between lead and following vehicles via advanced driver-assistance system. These fully automated platoons effectively eliminate the need for a driver in the trailing vehicles, thus offering significant potential labor cost savings for an industry struggling to attract qualified employees (Costello and Suarez 2015). Projects that have successfully demonstrated laterally and longitudinally automated platoons include SARTRE, PATH, Highway Pilot Connect, and Energy ITS.

The SARTRE project is unique because its developers anticipated the need to integrate truck platoons with connected passenger vehicle traffic. This project demonstrated the potential for platooning opportunities by creating a “road train” consisting of one lead truck and three following passenger vehicles, all equipped with lateral and longitudinal automation. Although drivers were present in the trailing passenger vehicles during the SARTRE demonstration, the drivers did not exert any control over their vehicles and were allowed to engage in nondriving tasks. Mixed platoons like these may be feasible as connected vehicle technology becomes more common in passenger vehicles. Moreover, the ability to platoon with various types of vehicles creates more opportunities for platoon formation, thus maximizing the potential benefits for fuel consumption and traffic flow.

TRUCK PLATOONING BENEFITS

Widespread adoption of truck platoons is expected to provide a variety of environmental, road capacity, traffic flow, and collision-safety advantages (Axelsson 2017; Kunze et al. 2011). These benefits depend on platooning trucks maintaining close following distances over an extended time, resulting in optimal aerodynamic drag reduction (Vegendla et al. 2015). A brief summary of recent studies investigating the potential environmental, traffic flow, and safety advantages of truck platooning is provided here to establish the critical performance characteristics of a successful platoon. Readers are referred to the cited articles for further technical details.

Fuel and Greenhouse Gas Emissions

Truck platoons with short following distances offer significant fuel savings by reducing aerodynamic drag on following trucks (Alam, Gattami, and Johansson 2010; Lammert et al. 2014). Although the lead truck does not share this advantage to the same degree, it receives minor benefits from the more consistent and economical speed profile provided by longitudinal automation. Estimates of fuel-saving benefits have varied across simulations and on-road tests, and actual yields vary with speed, following distance, and vehicle weight.

One test-track study showed fuel savings of 4.7 percent to 7.7 percent for platooning heavy vehicles with a gross vehicle weight of 88,000 lb (40,000 kg) using adaptive cruise control (ACC) to follow a heavier lead vehicle at 43 mph (70 km/h) (Alam, Gattami, and Johansson 2010). Another study of two identical, fully automated CACC-equipped heavy vehicles found a 4 percent overall improvement in fuel economy when traveling 50–75 ft (15–23 m) apart at a speed of 65 mph (105 km/h) (Humphreys et al. 2016). In Japan, a platoon of three CACC-equipped trucks traveling at 50 mph (80 km/h) with a gap of 33 ft (10 m) yielded a 14 percent mean reduction in fuel consumption compared to a manually driven single truck (Tsugawa, Kato, and Aoki 2011). In a platoon of two CACC-equipped trucks, fuel savings ranging from 2.7 to 5.3 percent were reported for the lead truck and 2.8–9.7 percent for the single following truck, yielding an overall team fuel savings of 3.7–6.4 percent (Lammert et al. 2014). In that demonstration, optimal performance was observed at 30 ft (9 m) following distances and a speed of 55 mph (89 km/h) for trucks weighing 65K lb (29,483 kg). Note that the results of these studies are based on demonstrations performed under ideal circumstances (e.g., straight, level roads with no additional traffic) and may represent an upper limit of performance. At the time of this writing, no data quantifying fuel economy improvements for automated truck platoons operating in normal traffic conditions could be identified.

Automobiles emit large amounts of pollutants through the consumption of fossil fuels, including carbon monoxide, hydrocarbons, carbon dioxide, particulate matter, and nitrogen oxides (Nasir et al. 2014). Among the gasses expelled by heavy vehicles, carbon dioxide (CO_2) is released in large amounts relative to the emissions of other vehicles; a European company attributed 17 percent of total CO_2 emissions to heavy vehicle operations in 2013 (OEM Off-Highway 2013). In the United States, combination trucks, which typically include a tractor with one or two semi-trailers attached to it, accounted for 77.1 percent of freight and 7.5 percent of total emissions in 2017 (Muratori et al. 2017). Based on energy consumption statistics reported in 2014 (Lammert et al. 2014), Muratori et al. (2017) estimated widespread deployment of truck platoons could reduce energy use by 4.2 percent.

Given this estimate, Muratori et al. (2017) projected a corresponding 0.22-percent reduction in annual CO_2 emissions in the United States. Another team estimated as much as an 11-percent reduction in annual CO_2 emissions for automated trucks in the United Kingdom maintaining a 26-ft (8-m) gap, with an equal increase in fuel savings (Davila and Ferrer 2014). Although this estimate is considerably higher than those of the studies described earlier and may represent an inflated projection, even moderate declines in heavy truck CO_2 emissions are desirable for reducing harmful environmental effects. The magnitude of positive environmental benefits would also grow with the global spread of automated technologies in both heavy goods and passenger vehicles.

Road Capacity

Although increased road capacity and improved traffic flow are expected benefits of truck platoons (FHWA 2021), the limited number of long-term truck platooning operations in live traffic has prevented thorough observation to quantify these effects. Simulations and models provide some sense of the conditions necessary to improve traffic flow with automated vehicle technology.

Using a microsimulation to compare the effects of passenger vehicle platoons operating under manual, ACC, or CACC conditions on road capacity, Zhao and Sun (2013) found that a greater overall proportion of CACC to non-CACC vehicles on a given roadway significantly increased traffic capacity. However, increasing platoon size (up to 10 vehicles) yielded only a minor benefit on road capacity, dependent upon increased levels of automated-vehicle market penetration. Another simulation found that a travel lane composed only of CACC-enabled passenger vehicles with a specific distribution of gap sizes between 0.6 s and 1.1 s produced significant improvements in road capacity as compared to the scenario where passenger vehicles were only equipped with ACC which showed insignificant change in the capacity of highways

(Shladover, Su, and Lu 2012). The authors explained that the lack of benefit for ACC vehicles may be attributed to the gap preferences preferred by their sample group, which closely matched preferences for manual driving and therefore nullified the advantages of automated longitudinal control. These preferences are also thought to be representative of the general population (Shladover, Su, and Lu 2012).

Together, the results of these projections suggest that significant benefits to road capacity may await greater market penetration of CACC technology. Until then, no significant advantages are apparent for increasing the length of truck platoons beyond their current limits of 2–4 vehicles; in fact, the challenges of performing lateral maneuvers with a larger platoon risk degrading rather than improving traffic flow (Zhao and Sun 2013).

Safety

Automated lateral and longitudinal control of heavy goods vehicles may potentially improve safety through improved reaction time and reduced collisions in comparison to human driving performance. In Germany, where running off-road, rear-end collisions, and side crashes comprised the three most common incidents on motorways, researchers estimated that advanced driver assistance systems (such as the ones utilized in the KONVOI project) had the potential to reduce incidents by more than 10 percent (Kunze et al. 2011). Notably, at the time of the analysis, 21 percent of crashes on German motorways were rear-end crashes with freight transport vehicles. Financially, a reduction in traffic incidents was estimated to correspond to savings equivalent to more than 532 million U.S. dollars (428 million euros) per year. However, achieving the benefits projected by Kunze et al. (2011) would be dependent upon a large percentage of trucks operating in platoons.

Truck platooning's main safety advantage is the automation of braking and, in some cases, steering, thus reducing human error. This advantage is significant because human error has been estimated to be a contributing factor in up to 95 percent of all crashes (Evans 1996). A study of New Zealand truck crashes in 2006 found that 18 percent of incidents were fatigue-related (Gander et al. 2006). Similarly, a case study of truck crashes in Kentucky occurring between 1998 and 2002 found that at least one of the two drivers involved in a light/heavy vehicle crash fell asleep or was fatigued. Fatigue increased the likelihood of a commercial vehicle crash being fatal by 14 percent. Driver distraction/inattention further increased risk by 31 percent (Bunn et al. 2005).

The direct transmission of data between lead and following vehicles in intelligent vehicle systems subverts these risks by allowing trailing trucks in a platoon to respond almost immediately to maneuvers made by the lead truck, limited only by the speed of the data transfer and its processing. In contrast to automated computer systems, human drivers must first perceive a cue that signals a change in the behavior of the lead vehicle (e.g., the illumination of brake lights or looming) and then decide on and carry out a response (e.g., swerving, braking). The speed of these responses is limited by the individual's alertness and physical reaction time and the physical distance between human interface devices and related vehicle components.

Reaction time is especially important in heavy combination vehicles, which require longer braking distances due to their weight and engine characteristics (Moridpour, Mazloumi, and

Mesbah 2015). The close following distances afforded by longitudinal automation systems limit opportunities to evade a forward collision by steering (Axelsson 2017). Therefore, emergency braking is most often evaluated to assess safety in automated truck operations. For the general driving population, average reaction time to unexpected roadway events was estimated at 1.6 s (Olson and Sivak 1986). Recent studies reveal a considerably shorter response time for current truck drivers performing emergency braking. One study conducted in a driving simulator found that truck drivers were able to apply emergency braking within an average of 0.6 s after the lead vehicle braked unexpectedly (Zheng et al. 2014). Another study on a live test track found that the truck driver in the second of a nonplatooning group of three identical trucks responded with emergency braking an average of 0.56 s after the lead vehicle began hard braking (Aki et al. 2014)[2] Reaction time for the driver in the third truck averaged 0.59 s. In a simulation of the same three trucks with automated platooning technology enabled, reaction time improved to an average of 0.39 s for the middle truck and 0.45 s for the last truck. Although this improvement may appear negligible, rear-end collisions between following trucks, which occurred in 60–80 percent of manual control trials, were completely eliminated with the implementation of automated longitudinal control.

The effectiveness of safety maneuvers is further facilitated by the maintenance of safe and consistent following distances, which have been associated with reduced crash risk (Lank, Haberstroh, and Wille 2011; Fairclough, May, and Carter 1997). These capabilities support the potential safety benefit of CAV control over the performance of human drivers. However, the live braking performance reported in the study by Aki et al. (2014) was observed under ideal conditions, when drivers were presumably alert and aware that their responses were being measured.

LIGHT-VEHICLE DRIVERS' BEHAVIOR

Until recently, human factors research related to automated truck platoons has focused almost exclusively on the experience of the heavy-vehicle driver. Common research topics in this area include gap acceptance within a platoon, emergency maneuvers within a platoon, cognitive demand on heavy vehicle drivers, and factors related to an automated system user interface, such as trust and acceptance (Nowakowski et al. 2010; Aki et al. 2014; Zheng et al. 2014; Lank, Haberstroh, and Wille 2011; Hjälmdahl, Krupenia, and Thorslund 2017). The issues addressed in this research are critical to the successful, safe, and efficient operation of automated truck platoons and posed the first human factors barriers to their deployment.

However, a considerable gap remains in the literature related to the effects of truck platooning on light-vehicle drivers. These impacts should be assessed and evaluated before the large-scale deployment of truck platooning because, as previously mentioned, light-vehicle drivers' behavior may significantly affect platoon performance, potentially compromising financial and environmental advantages.

Maneuvers such as merges and cut-ins can also pose safety risks for passenger-vehicle and automated-truck drivers alike. In addition to safety concerns, acceptance of truck platoons by

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[2] To maintain the safety of the drivers, trucks traveled side by side in adjacent lanes at distances that would be used in a platoon formation. No automated or connected technology was enabled during these tests.

light-vehicle drivers is likely to be an important factor for securing the continued social and financial support of the agencies funding the development of these technologies (European Automobile Manufacturers Association 2016). Given these concerns and the pace at which deployment is currently progressing, identifying the potential hazards and challenges that will be encountered by light-vehicle drivers traveling near and around truck platoons is essential for establishing safe and appropriate practices for both platoon and nonplatoon vehicles. Potential solutions may include behavioral guidance, modifications to operational characteristics of the truck platoon, or policies regulating the platoon's operation that do not significantly reduce its ability to perform efficiently.

In the future, CAV technology will likely be able to mitigate many of the behavioral issues discussed here by providing timely and personalized guidance to nonplatoon vehicles near a truck platoon. However, significant market penetration of V2V or connected vehicle technologies is expected to occur later for passenger vehicles than for trucks (up to 5 yr later) (Hendriks, van Heijningen, and Jorna 2017). Therefore, this review assumes that light-vehicle drivers' vehicles will not be equipped with intelligent or automated features that allow in-vehicle communication regarding the driver's environment during early platoon deployment.

TRUCK LANE RESTRICTIONS

To mitigate conflicts between trucks and light-vehicle drivers and reduce effects on traffic flow, State DOTs have implemented dedicated or managed truck lanes in some areas. Similar to dedicated lanes proposed for connected vehicles, these strategies can potentially reduce merge conflicts, cut-ins, and the negative psychological effects associated with truck interactions. However, these lanes can have detrimental effects if not carefully implemented.

As an example of a positive effect, restricting trucks to a specific travel lane was shown to decrease the number of lane changes performed on a freeway in Florida (Mugarula and Mussa 2003). Simulations that calculated the effects of truck lane restrictions and dedicated truck lanes on lane changing, merging, and rear-end conflicts with passenger vehicles on an expressway in a major Canadian city also showed that a dedicated truck lane could reduce lane changing and merge conflicts between light-vehicle drivers and heavy vehicles (El-Tantawy et al. 2009). However, this change also produced an increase in conflicts involving trucks merging onto the freeway. Implementing a leftmost dedicated truck lane in the simulation reduced lane-merging conflicts but increased lane-changing problems. The authors noted that lane-changing conflicts occur more frequently than merging conflicts and suggest that restricting trucks from the left two lanes may be more beneficial than a leftmost dedicated lane for trucks. These regulations were found to be most effective when the percentage of truck traffic exceeded 15 percent.

KNOWLEDGE OF TRUCK PLATOONING OPERATIONS

As mentioned previously, behaviors that put light-vehicle drivers at risk when operating near trucks may stem from an underlying misunderstanding of truck operations. A similar problem was identified and addressed in the United States in the 1980s, when the "Share the Road" highway safety campaign, sponsored by the American Trucking Associations, attempted to improve driver knowledge and education regarding trucks to improve driver safety (American Trucking Associations 2023).

This program resulted in increased outreach and media efforts to teach the public how to drive safely around large trucks, including reduced cut-ins and maintenance of longer following distances. Similarly in 2004, Washington State applied the National Highway Traffic Safety Administration's High Visibility Enforcement model from the "Click it or Ticket" seatbelt campaign to reduce unsafe driving behaviors around commercial motor vehicles (Thomas et al. 2008). Washington State implemented the Ticketing Aggressive Cars and Trucks (TACT) program on four high-crash interstate highway corridors (approximately 25 mi in length) for 18 mo. On the two corridors that received TACT media messages and increased enforcement, drivers' familiarity or exposure to TACT messages increased from about 18 percent to 67 percent over the course of the study. Drivers were presented with messages directing them to leave more space when passing trucks. Subsequently, the number of people who said they adhered to this guidance rose from 16 percent to 24 percent at intervention sites, whereas no change was observed at control comparison sites. Violation rates also decreased significantly at intervention sites (from 46 percent to 23 percent) while remaining constant at control locations.

The results of the study support the hypothesis that messages were received and understood by drivers, which led to a change in knowledge and modified behavior in the intended direction. During early exposure to automated truck platoon operations, similar educational strategies may be useful, particularly in locations where truck platoons are expected to operate frequently.

PLATOONING INDICATORS

Allowing light-vehicle drivers to distinguish between manual and platooning trucks may be the first step in improving compatibility and understanding among truck platoons and light-vehicle drivers. Stevens, Mccarthy, and Gilhead (2014) argued for the need to support appropriate behavior among light-vehicle drivers by giving them a way to: 1) recognize platoons, possibly via distinguishing signage; 2) have access to information and publicity; and 3) receive advice for maneuvers such as overtaking and merging.

Van Loon and Martens (2015) explored one challenge to facilitating compatible interactions between truck platoons and manual vehicles, particularly during the early period of deployment. In their paper, the authors discussed a fundamental issue expected to arise from manual and automated vehicles sharing the road: forward compatibility, in which light-vehicle drivers may miss or respond inappropriately to the behavior of an automated vehicle. Human drivers may also expect human-like behavior from truck platoons when, in reality, much of the trucks' behavior will be automated. Automated vehicles' information must be communicated to unequipped vehicle drivers in a clear and timely manner not reliant on connected technologies. Since near-term automation will control some, but not all, vehicle functions in limited situations, visual indicators need to adaptively reflect these changes as they occur (e.g., when a vehicle is actively platooning). Providing a visual cue to light-vehicle drivers may be a key component in guiding appropriate driver behavior because this cue allows drivers to recognize situations where platooning-specific behavioral protocols are in effect.

Precedent for visual indicators to denote nonstandard vehicle operations currently exists on modern-day roads. In an example highly relevant to truck platoons, static signs are often used to denote nonautomated convoys of vehicles traveling on public roads. These signs include "Convoy follows" on the front of the lead vehicle and "Convoy ahead" on the rear of the last vehicle (U.S. Army 1995). Vehicle-mounted flags also denote each element of a convoy, with different colors signifying various platoon positions and duties. Rotating amber warning lights placed on the first and last vehicles in the convoy, as well as heavy machines or oversized or overweight vehicles, warn light-vehicle drivers to use caution when navigating around these vehicles. Such signs and signals allow both platoon and nonplatoon vehicles to easily identify the start and end of the convoy and call attention to potential hazards.

Some truck platoon demonstrations have used messages displayed on the sides and rear of the truck trailer to imply automated following between platoon vehicles (Wolters 2016). The truck platoons in the EU Truck Platooning Challenges displayed messages along the side of tailing platooning trailers stating that "This truck is connected to the next truck" and "This truck is the leader" on the side and rear panel of the lead vehicle. Rear panels on the following trucks displayed "The future is ahead of you."

When testing automated passenger vehicle operations, research teams at TFHRC have employed horizontal bars of strobing lights mounted at the top of the front and rear windshields (FHWA 2016). These lights activate to indicate automated control and change colors to identify specific automated operations. However, the meaning of these signals was known only to the researchers for the purposes of verifying vehicle functions during testing. Messages and signals such as strobing light bars are likely too vague to be informative to light-vehicle drivers, particularly those who are unfamiliar with CAV technologies. Furthermore, this level of information fails to guide light-vehicle drivers' behavior in the vicinity of the platoon. Finally, given the adaptive nature of CACC platooning technology, light-vehicle drivers will benefit from the development of changeable signals capable of representing dynamic shifts between active platooning and manual driving.

CONCLUSIONS

The literature review identifies several relevant variables that are likely to be important for predicting and manipulating light-vehicle driver behaviors in the presence of truck platoons. The most relevant variables fall into the following categories: 1) truck-platoon operations, 2) entering or exiting the freeway, and 3) knowledge of platoon operations.

Truck Platoon Operations

Previous research and demonstrations illustrate the potential challenges of light-vehicle drivers operating near strings of large vehicles. Light-vehicle drivers' reactions to the number of automated trucks in a platoon should be investigated because how light-vehicle driver behaviors may change in response to, for example, two standard-size platooning trucks compared to three, is unclear. Currently, near-term platoon deployments will likely include two or three trucks, with four as a rare occurrence. Researchers also need to identify gap lengths within the platoon suitable both for efficient platooning operations and the safety of light-vehicle drivers. Optimal gap distance should be small enough to provide substantial traffic and fuel savings benefits while also preventing or minimizing cut-ins by light-vehicle drivers. A systematic investigation of both commonly used and extreme gap lengths will help to establish safe, optimal standards for platoon operations prior to full deployment. Researchers should also consider and evaluate travel speed for its influence on cut-ins, as drivers may feel comfortable merging into a smaller gap distance at lower speeds.

Entering or Exiting the Freeway

Substantial simulated and real-world evidence exists to suggest that merging onto or off the freeway in the presence of an automated truck platoon will pose navigational and operational challenges for both platooning and nonplatooning vehicles. De Waard, Kruizinga, and Brookhuis's (2008) work on merging near truck columns could be extended to include a simulated automated truck platoon with predetermined gap sizes to observe light-vehicle drivers' strategies for entering the roadway. Potential interventions to facilitate successful and safe roadway entry may also be tested (e.g., ramp meters, intentional gap lengthening within the platoon when nearing a merge point). Researchers should examine subsequent effects on light-vehicle drivers attempting to exit the freeway, whether to reach an assigned destination or respond to a temporary event (e.g., detour, lane closure). Researchers should also assess the degree of sign occlusion caused by an automated truck platoon of varying lengths. In addition, self-report surveys and questionnaires such as the NASA Task Load Index or Rating Scale of Mental Effort can measure the cognitive effort and stress levels of light-vehicle drivers.

Knowledge of Platoon Operations

As previously discussed, a necessary precursor to facilitating appropriate light-vehicle driver behavior is making platooning vehicles identifiable. Researchers should design signs and signals to indicate active truck platooning and test for their clarity, level of information, adaptability, and comprehension. Researchers should carefully consider the location, content, and format of the indicator(s) (e.g., flashing light, text display, static symbol) to balance feasibility, cost, and effectiveness. Light-vehicle drivers' access to general knowledge of automated truck platooning operations can also be manipulated to study its effect on driving behavior. Researchers should identify the level of knowledge most likely to allow light-vehicle drivers to recognize the truck platoon (with or without an external indicator) and subsequently encourage performance of proper merging maneuvers near the platoon. Visual indicators and/or general knowledge may be combined with any or all of the discussed topics to compare behavior of drivers with prior knowledge of operations to that of naïve drivers. Driver age and gender should also be considered, as effective solutions should be similarly comprehensible for most drivers.

Due to possible variations in behavior related to demographic variables, researchers need to study these reactions directly and at an individual level rather than through simulations, which depend on generalized models of driver behavior. Given the scarcity of operational automated truck platoons, the extreme risk posed by the uncertainty of light-vehicle driver reactions, and the nature of close following distances between platooning trucks, a driving simulator is probably the most appropriate method for investigating these behaviors. By studying these variables in a safe, controlled environment, researchers can gain insight into the predicted behavior of light-vehicle drivers operating near truck platoons. The identified safe and desirable actions in such situations can then be encouraged by modifying the platoon operation and/or by guiding light-vehicle drivers to appropriate behaviors. By contributing to the proper preparation and education of automated truck operators and light-vehicle drivers, this research can support the safe and successful adoption of truck platoons in the future.

CHAPTER 3. LIGHT-VEHICLE DRIVER PERCEPTIONS OF TRUCKS

This chapter presents an overview of the survey conducted to provide a baseline of driver understanding and attitudes upon which to develop studies to investigate driver responses near simulated platooning trucks.

As commercial truck platoons near public deployment, researchers need to assess how light-vehicle drivers' understanding of truck operations may change around semiautomated groups of closely following trucks. Due to their size and limited braking and acceleration rates, trucks pose several safety risks for light-vehicle drivers. CAV systems have a high potential to mitigate these risks. However, when two or more trucks maintain consistently close following distances during long periods of CACC platooning, potential dangers may become more prevalent for light-vehicle drivers. On the other hand, near-term platooning operations with only two or three trucks may appear very similar to current-day conventional trucking. Therefore, a questionnaire was designed to target several key research questions:

- How do drivers typically perceive trucks, understand truck movements, and behave near single conventional trucks?
- How do drivers perceive trucks and behave near two or more conventional trucks with various gap distances?
- How do drivers decide that two or more trucks are intentionally following each other or traveling together?
- How does the awareness of automated technology affect drivers' stated behavior and perceptions of truck safety?

METHOD

The following section describes data collection methods and the survey distributed to participants.

Procedure

The questionnaire contained images of real trucks on highways and was divided into six sections:

- Single conventional trucks.
- Two trucks with a larger gap distance that appeared to be more than one car's length.
- Two trucks with a smaller gap distance of approximately one car's length.

- Four trucks with minimal gap distances that were significantly less than one car's length between each.
- Description of CACC automated truck platooning.
- General attitudes toward automated or advanced driver-assistive vehicle technology.

For each section, participants responded to a combination of forced-choice and open-ended questions on their judgment of truck safety, their own safety, following behavior of the truck, and statements regarding their likely behavior around the trucks depicted or described.

Participants

Survey respondents included 50 licensed drivers from the Washington, DC, metropolitan area (32 females, 18 males). Most participants (68 percent) were younger than 46 yr. Two participants reported previous experience as a truck driver or with driving heavy vehicles such as freight trucks, with one stating a 2-mo tenure in the early 2000s and the other reporting a 6-yr tenure ending in the 1990s. Responses from the two participants were generally neutral-to-positive and did not appear to meaningfully vary from the rest of the sample, so these responses were retained in group analyses. The questionnaire was distributed at two local community hubs; volunteer respondents were paid $10.

ANALYSIS RESULTS

In the following analyses, "driver safety" refers to the participants' sense of their own safety near a truck, and "truck safety" refers to the safety of the trucks themselves and/or the drivers operating them. Questions regarding naming of grouped trucks are presented in aggregate at the end of the Conventional Trucks section. Selected rating questions were analyzed using a generalized estimating equations (GEE) model (Liang and Zeger 1986) assuming a normal distribution. For each analysis, the report authors identified valid responses as those which were legible and reasonably addressed the question asked. Null responses for individual questions, or when a participant failed to provide a response, were excluded from analyses.

Conventional Trucks

When participants were asked to describe general feelings when driving near or around single heavy trucks (figure 1), 54 percent of the responses were negative and noted feelings of anxiety or fear. Forty-four percent of the responses were neutral, with some statements about caution or awareness. Most participants (91 percent) reported that their driving behavior differs around trucks compared to other passenger vehicles. Of these, 44 percent of responses mentioned intentions to pass or otherwise distance themselves from trucks, and 21 percent described an increased awareness or avoidance of truck blind spots. General caution was mentioned in 33 percent of responses noting a change in behavior.

Left: © 2009 Madden/Wikimedia Commons; right: © n.d. Sardá/PublicDomainPictures.net.

Figure 1. (a) Left. Photograph. Front side view of single conventional truck on the highway (Madden 2019); (b) Right. Photograph. Rear side view of single conventional truck on the highway (Sardá n.d.).

Responses also reflected negative perceptions of single conventional trucks in the terms chosen to describe trucks. More than 65 percent of the terms chosen were associated with negative characteristics. On a scale of 1 (very unsafe) to 5 (very safe), the mean rating of driver safety when near a single truck was slightly unsafe at 2.68 (standard deviation = 1.13). Statistical analysis revealed a significant effect of gender on driver safety rating when driving near single conventional trucks: The probability of females choosing the "very unsafe" response option was 5.28 times greater than that of males, $\chi^2(1) = 10.12$, $p = .0015$.

Participants were then shown two trucks with similar container markings traveling in the left lane with what appeared to be more than a car's length between them (figure 2). As with single conventional trucks, 54 percent of responses described negative reactions such as nervousness or fear. Forty percent of responses were neutral, and 6 percent were positive.

© 2007 Futureatlas.com/Flickr. Image cropped by authors.

Figure 2. Photograph. Two commercial trucks in the leftmost lane of a highway (Futureatlas.com 2007).

As an alternative method of inferring judgments of intentional following, the study authors asked participants what they thought the following truck would most likely do if the lead truck changed lanes. Respondents who perceived the trucks to be following each other were expected to be more likely to believe the second truck would change lanes behind the front truck. This option was chosen in 67 percent of the 49 valid responses for the first truck pairing.

Respondents then rated the distance between the trucks on a 5-point scale (1 = much shorter than average and 5 = much longer than average) and truck safety and driver safety (1 = very unsafe and 5 = very safe). When shown a picture of two commercial trucks in the leftmost lane, participants rated the mean truck-gap distance as 2.96, corresponding to typical/average (standard deviation = 0.75), a mean truck safety rating of 3.54, between neutral and somewhat safe (standard deviation = 1.00), and a mean driver safety rating of 3.06, indicating neither safe nor unsafe (standard deviation = 1.14).

Participants then answered the same questions regarding an image depicting two trucks in the rightmost lane of a three-lane highway (figure 3). These trucks had a shorter apparent gap distance of approximately one car-length. The markings on each truck trailer were dissimilar from one another. Sixty-two percent of participants reported negative feelings when driving around trucks like those shown. Thirty percent of responses were neutral, and 8 percent were positive. Two of the positive comments referenced trucks remaining in the right lane, leaving two lanes open for the driver to maneuver around them. Branding and markings on the truck containers were mentioned in several explanations for whether the trucks were seen to be following or not. In this case, dissimilar truck markings were noted as an indicator that the trucks were not traveling in a group.

© 2017 Pxhere.com.

Figure 3. Photograph. Two trucks traveling in the rightmost lane of a three-lane highway (Pxhere.com 2017).

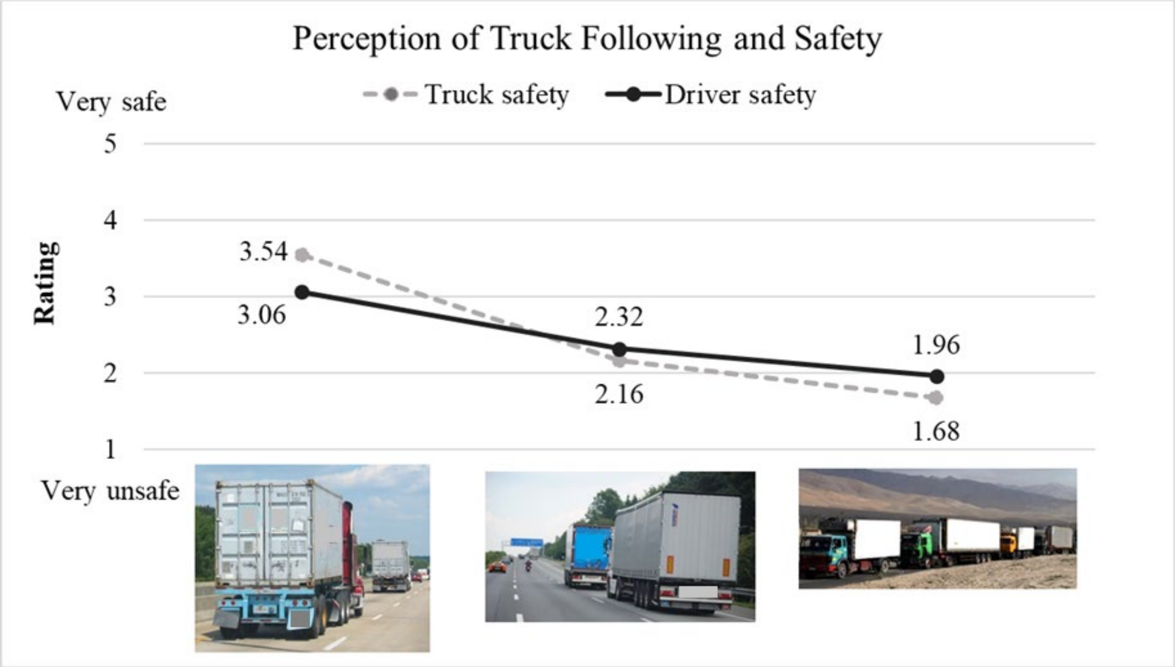
When participants were asked how the second truck would respond if the first truck changed lanes, 35 percent of the 48 valid responses indicated that the second truck would change lanes behind the first truck. The mean truck gap distance rating was 1.84, suggesting slightly shorter than average (standard deviation = 0.77), the mean truck safety rating was 2.16, corresponding to somewhat unsafe (standard deviation = 0.10), and the mean driver safety rating was 2.32, indicating somewhat unsafe (standard deviation = 1.10).

In the final example, a series of four trucks distinctly colored with various markings were depicted traveling in the left lane of a rural road (figure 4). The trucks had a minimal gap distance with significantly less than a car's length between each. Most participants (68 percent) reported negative feelings when asked to imagine driving near or around the trucks depicted. Slightly more than half of respondents (56 percent) expected the second truck to change lanes behind the first truck. The mean truck gap distance rating was 1.22, or much shorter than average (standard deviation = 0.68); the mean truck safety rating was 1.68, between very unsafe and somewhat unsafe (standard deviation = 0.10); and the mean driver safety rating was 1.96, indicating somewhat unsafe (standard deviation = 0.99).

© 2010 Resolute Support Media/Flickr. Image cropped by authors.

Figure 4. Photograph. Four trucks with minimal gap distance on a rural highway (Resolute Support Media 2010).

Across all three images depicting two or more trucks, a trend appeared in the perceived truck-gap distance and perceived safety of both the trucks and surrounding drivers (figure 5). However, a change in the probability of changing lanes associated with truck-gap distance was not noticeable; the second truck was generally expected to change lanes behind the first truck, with this probability being slightly lower for the second example image compared to the other two (table 2).



Left: © 2007 Futureatlas.com/Flickr; center: © 2017 Pxhere.com; right: © 2010 Resolute Support Media/Flickr.

Figure 5. Graph. Mean ratings for truck gap distance, truck safety, and driver safety.

Table 2. Mean distance ratings and following response options.

Image	Truck Gap-Distance Rating	Following
	2.96	2.00
	1.84	1.80
	1.22	1.81

Top: © 2007 Futureatlas.com/Flickr; middle: © 2017 Pxhere.com; bottom: © 2010 Resolute Support Media/Flickr.

Note: Ratings are on a scale of 1 (much shorter than average) to 5 (much longer than average), with larger numbers indicating greater truck-gap distance. The options provided for the following truck were: 1 = The second truck would continue in its current lane; 2 =The second truck would change lanes behind the first truck; and 3 =The second truck would remain in its current lane, speed up, and pass the first truck.

Statistical analysis of the rating of gap distances between the trucks across each image revealed significant differences at a 95 percent confidence interval, $\chi^2(2) = 159.62$, $p < .0001$. Truck-gap distance ratings decreased significantly across the progression of the three image examples; the ratings also showed a significant effect of age group, with older respondents being 3.2 times more likely to rate an image as "much shorter than average" than younger respondents, $\chi^2(1) = 8.50$, $p = .0036$. No significant differences were associated with gender.

The differences between all three truck safety ratings for each image were significant, $\chi^2(2) = 105.64$, $p < .0001$. Differences in driver safety ratings were also significant, with ratings for the second and third image significantly lower than those for the first image, $\chi^2(2) = 45.26$, $p < .0001$. Ratings of truck and driver safety were significantly associated with gender, $\chi^2(1) = 10.19$, $p = .0014$. Females were 3.32 times more likely than males to rate trucks as "very unsafe". Similarly, on average, $\chi^2(1) = 7.68$, $p = .0056$, females provided significantly lower driver safety ratings than males. Compared to males, females were 0.74 times more likely to rate driver safety as "very unsafe." Age group was not significant for either safety category.

At the end of each portion, participants were asked what potential benefits and risks they thought might arise, assuming that the trucks depicted were intentionally traveling together as a group. A large portion of respondents did not indicate any expected benefits. However, those who stated benefits typically mentioned improved efficiency (both for fuel use and the amount of cargo carried), more convenience, reduced chances of a truck getting lost on its route, and enhanced ability for light-vehicle drivers to predict whether trucks would remain in the same lane.

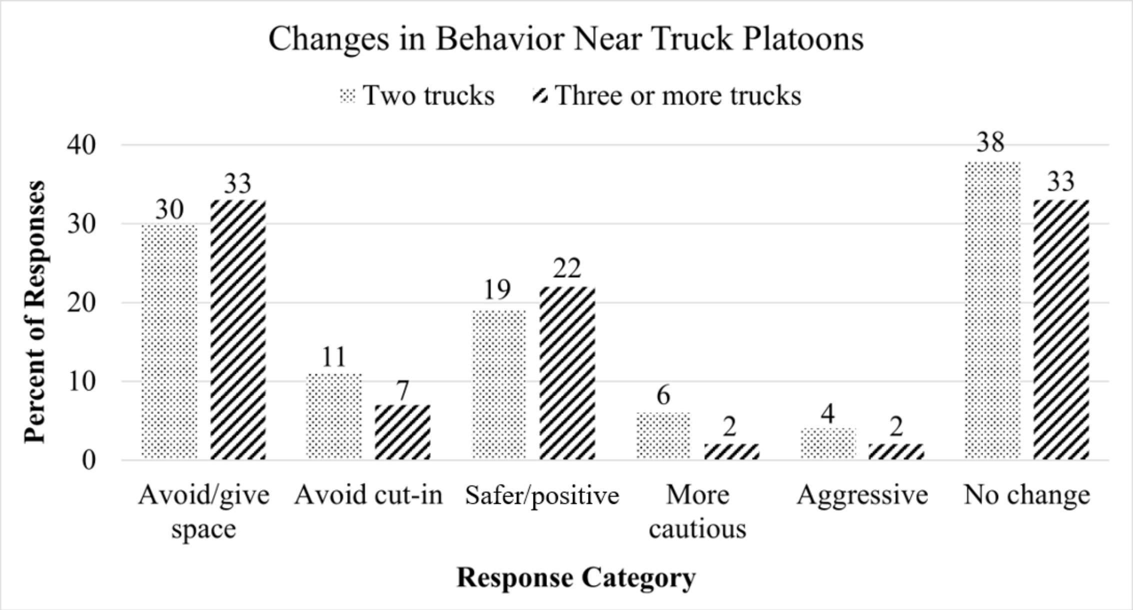
Across all three example images, collisions comprised most of the expected risks. Concerns regarding mobility (e.g., trucks causing traffic jams or making it difficult for light-vehicle drivers to change lanes) were secondary and visibility (that of the truck drivers or of light-vehicle drivers) tertiary. Risks involving the behaviors of light-vehicle drivers, such as speeding around or cutting-in between trucks, were more frequently noted for the first example image than the other two. Participants indicated that both the challenges of navigating around trucks in the left lane as well as the space between the trucks influenced these concerns.

Automated Trucks

After answering questions pertaining to conventional trucks, participants were provided a description of CACC and automated truck platoons. The description explained that 1) sensors and communication technology allow equipped trucks to maintain close following distances, 2) drivers in the trucks can enable and disable the system, and 3) long periods of close following at steady speeds are expected to reduce pollution and fuel consumption. Respondents were asked about their perceptions of the technology and their familiarity with automated vehicle systems. Of the 44 valid responses, 59 percent mentioned positive consequences of automated truck platooning, 27 percent were neutral, and 9 percent mentioned negative consequences. Several responses noted concerns about the reliability of the wireless connectivity between the trucks. Some participants were concerned that truck drivers would be more susceptible to distraction. Sixteen percent of valid responses described the automated platoon as being more predictable via fewer lane changes or more consistent expectations of lane occupation. Two respondents

(5 percent) described an expectation that signs or warnings would appear on the automated trucks.

When asked to rate the importance of knowing a platoon of trucks was nearby (1 = very unimportant; 5 = very important), the mean rating for a two-truck platoon was 3.61 (standard deviation = 1.06) and 3.63 (standard deviation = 1.18) for a platoon of three or more trucks. Figure 6 summarizes behaviors and perceptions that are expected to change around platoons of two, three, or more trucks. The greatest number of responses indicated no expected changes near a two-truck platoon compared to conventional trucks. For both two- and three-truck platoons, a large portion of responses mentioned avoiding the trucks or creating distance between the trucks and the light-vehicle driver, and roughly 20 percent of responses indicated positive perceptions. Several participants specifically described avoiding cut-ins between platooning trucks. Across both two- and three-truck platoons, a small proportion of responses (approximately three percent) suggested that drivers may take advantage of the enhanced predictability of automated trucks by driving more aggressively around platoons.



Source: FHWA.

Figure 6. Graph. Distribution of changes in perception and behavior associated with length of truck platoon.

Participants ranked the current status of the trucks' operation mode as the most important information to receive. Other information, such as the roads where truck platoons might be operating, the number of trucks in a platoon, and the exact location of platooning trucks, were similarly rated as less important.

Participants then viewed four experimental signs designed to inform drivers of the presence or operation of truck platoons (figure 7). The survey informed respondents that signs A and D were standard static signs that do not change, regardless of the truck's operating mode, whereas signs B and C become "active" or light up when the truck engages the automated travel mode.

Source: FHWA.

Note: Arrows indicate transitions from inactive to active status for dynamic electronic signs.

Figure 7. Illustrations. Experimental signs to notify drivers of the presence or operation of automated truck platoons.

The next question asked participants to assign the letter (A, B, C, D) corresponding to a sign to each of the following four statements, based on which sign they thought best fit each statement:

- The *most effective* if it appeared *on a truck* capable of operating in the mode described before.
- The *least effective* if it appeared *on a truck* capable of operating in the mode described before.
- The *most effective* if it appeared *on the side of a road* where trucks may be operating in the mode described before.
- The *least effective* if it appeared *on the side of a road* where trucks may be operating in the mode described before.

Sign B was rated as most effective as a truck-mounted sign (37 percent of responses), and sign A was rated as most effective as a roadside sign (47 percent of responses). Sign B was notably ranked high as both most effective for trucks and least effective for roads.

Next, participants answered a series of questions about their knowledge and perceptions of automated vehicle technology. In 82 percent of responses, participants expected a driver to be present in an automated vehicle. General feelings toward automated vehicle technology were neutral/indifferent at a mean of 3.48 (standard deviation = 0.95). The perceived safety of automated vehicles was also near the middle of the range with a mean of 3.18 (standard deviation = 1.02). However, the indication that most but not all respondents expected a human driver to be present in an automated or semiautomated truck may have influenced these and other responses. On average, respondents had roughly heard of 3 out of 6 advanced vehicle technologies, with automated braking and ACC familiar to the largest proportion of respondents. CACC and connected vehicles—terms frequently associated with automated truck platoons—were the least represented in these responses.

Finally, only one participant had heard of truck platoons prior to the survey. When asked to describe the meaning of an automated truck platoon, 26 percent of total participants were unsure or provided invalid responses. Of the 48 valid responses collected (74 percent of total responses), 35 percent described a partially automated platoon in which drivers were present, which aligned with the CACC platoon description provided in the survey. Twenty-seven percent of responses were coded as partial or incomplete matches with the survey description. Fifteen percent of responses indicated that the trucks were driverless and/or remotely controlled, and 23 percent of responses indicated the participant was unsure. However, the phrasing of "automated truck platoons" used in the question may have influenced participant responses; using the terms partially automated or semiautomated platoons may have yielded different results.

Naming

For each of the three images of two or more conventional trucks shown, participants were asked to provide a name for the group of trucks, with an assumption that the trucks were intentionally following one another. Across all three images, the term "convoy" was the most frequent, 76 percent of total responses. The second most common term was "caravan," at 58 percent. The number of "caravan" responses appeared to become slightly more frequent with the increasing proximity and/or number of trucks across the three images.

Free responses did not reveal consistent patterns in naming convention for single automated trucks; most responses suggested that the term "truck" remained appropriate, although some participants offered names that combined this term with others to suggest its connected/automated nature, such as "connected," "auto-follow," "semiautomated," "smart," "wireless," or "semi-self-driving." "Convoy" (23 percent) and "caravan" (13 percent) were again listed as free-response names for groups of automated trucks.[1] Unlike with conventional trucks, names including the term "train," such as "road train," comprised 13 percent of responses. Notably, one respondent explained that the term "train" was preferred for automated trucks due to their existing understanding of a convoy as a group of several independent trucks. The terms "automated" and "wireless" were sometimes combined with other terms, such as "convoy" or "caravan."

In regard to automated trucks, most participants (35 percent) chose to identify automated trucks as "semiautomated vehicles" when asked to choose from a list of applicable terms. "Smart vehicle" was the second most common choice at 33 percent of responses. When asked to choose terms from a predefined list, most respondents (72 percent) preferred the term "convoy" for a group of automated trucks and "linked" for a single automated truck operating within a group of multiple trucks.

DISCUSSION

Researchers distributed the survey to a sample of typical drivers to learn more about their perceptions and attitudes toward heavy trucks, truck-following behavior, and automated heavy vehicle technology. Participants viewed three static images depicting single or multiple trucks with varied markings, gap distances, and lane occupancy. Respondents were then asked how their attitudes and behavior might differ near a CACC semiautomated truck platoon and which characteristics of a platoon they would be most interested in knowing. Participants also reported

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[1] Participants spelling and hyphenation of terms varied for terms such as semiautomated ("semi-automated").

on naming conventions for single and grouped conventional and automated trucks through a mix of open and forced-choice questions. Finally, participants reported on their familiarity with and general attitudes toward advanced driver-assistance systems and automated vehicle technology.

Overall, the results of the study suggest that most drivers are wary when driving near single conventional trucks, are mindful of truck-driver blind spots, and tend to assign negative attributes to trucks on the roadway. Perhaps for these reasons, most respondents indicated a preference to avoid trucks or create space between themselves and trucks, either by adjusting speed or changing lanes. Driver perceptions of comfort and truck behavior were shown to vary with the gap distance between multiple trucks as well as travel lane occupancy. Although judgments of intentional following appeared to vary with truck markings and travel lane, truck-gap distance did not appear to have a strong effect on driver's perception of truck grouping unless the gap was very small. Judgments of following based on lane changes may have been influenced by the lane in which the trucks were shown (i.e., two trucks changing lanes together was more probable when moving from a left lane to a right lane and less probable when moving from right to left, except when minimal distance was held between the trucks). Notably, several participants described rear trucks with close following distances as potentially aggressive. Although the interpretations may have been influenced by the limited context created by a static image, these assessments illustrate how drivers may judge the behavior of a typical conventional truck to be independent and potentially dangerous to surrounding vehicles. Given the overall negative associations with conventional trucks and the potential benefits of automated platooning, a targeted outreach campaign may improve public perception of trucks, which could extend to greater acceptance of semiautomated platoons.

When provided with a description of CACC automated truck platoon technology, respondents indicated that they would expect automated trucks to be more predictable than conventional trucks by remaining in their travel lane and maintaining consistent following patterns, thus reducing some safety concerns associated with conventional trucks. Almost half the participants thought that automated vehicles are somewhat safe or very safe, and 60% of participants felt automated vehicle technology to be somewhat positive or very positive. These responses reflected an increased perception of safety or a positive attitude toward automated following trucks. Participants also indicated that they would continue or increase efforts to give space to automated truck platoons, with some explicitly mentioning avoiding cutting-in between platooning trucks. These findings suggest that awareness of automated technology in a group of closely following trucks has the potential to change light-vehicle drivers' perceptions and behavior near platoons. Adding signage or marking partially automated truck platoons may have meaningful benefits for light-vehicle driver safety and comfort while also preserving the intended operations of the platoon. Such indicators may work in conjunction with outreach campaigns to improve public understanding and awareness.

To encourage desired light-vehicle driver behavior, an effective indicator of truck platooning may need to communicate one or more of three characteristics: 1) trucks within a group are intentionally following each other; 2) trucks within a group are intentionally maintaining short gap distances, and 3) trucks are equipped with automated vehicle technology to safely maintain short gap distances. Responses to questions regarding naming conventions revealed that "convoy" and "caravan" (though slightly less common) are well-known terms for a group of two or more conventional trucks. Therefore, the term "convoy" should be sufficient to indicate a group of multiple trucks following one another. Survey results suggested that the distance between trucks was less important for driver behavior and perceptions of safety and that the awareness of automated vehicle features could be sufficient to dissuade concerns regarding close truck-gap distances. The terms “semiautomated,” “linked,” and “smart” were frequently chosen to describe automated vehicle technology in a CACC platoon and may serve to distinguish a truck platoon or “convoy” as different from a typical group of independent, conventional vehicles. Despite the term “automated truck platoon” being mostly unfamiliar to the participants surveyed, their descriptions of the term were fairly accurate (62 percent accurate or partially accurate). Although this accuracy may be due to the description provided in the survey, researchers should determine whether drivers unfamiliar with this terminology are able to correctly interpret and respond to this naming convention, given its popularity in technical fields.

The signs shown in figure 8 draw upon the findings of the truck perceptions survey. These signs communicate automated vehicle technology and truck following through symbols, text, or a combination. As reflected in sign-preference responses collected in the survey, truck-mounted signing will be limited to dynamic signs capable of indicating when platooning is engaged. Roadside-mounted signing includes both static and dynamic message signs. Signs R3 and T3 are proposed as comparisons for the specificity of other signs and to determine whether minimal and potentially unfamiliar information will be sufficient to encourage appropriate driver behavior and positive perceptions. These signs were further used in the following studies discussed next to investigate comprehension and response to novel automated truck signing.

Roadside-mounted

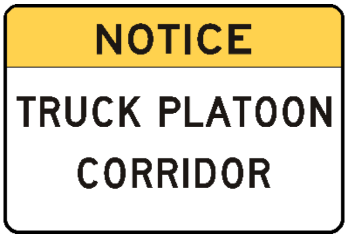
Truck-mounted


R1

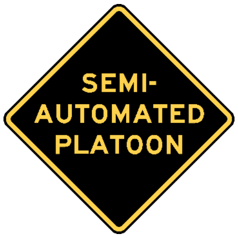

T1

R2

T2



R3



T3

All images source: FHWA.

Figure 8. Illustrations. Proposed designs for platoon signing (Roldan and Gonzalez 2021).

CHAPTER 4. SIGN LAB STUDY ON EFFECTIVE INDICATORS OF PARTIALLY AUTOMATED TRUCK PLATOONING

As automated vehicles move toward public deployment, the question remains regarding how they will safely and efficiently interact with light-vehicle drivers and particularly manually driven vehicles. This issue may be particularly important during the early stages of automated vehicle deployment, when automated vehicles are less likely to be fully self-driving and/or common on roadways. During these stages, light-vehicle drivers will be expected to safely interact with partially automated vehicles that may act differently than manually driven vehicles (Schieben et al. 2019). The ability to recognize partially or fully automated vehicles in mixed-fleet traffic may support drivers in adjusting their behavior and expectations.

Building off the results in the truck perceptions study described in chapter 3, this chapter describes an experiment that explored the effectiveness and influence of signed automated-truck platoons on light-vehicle drivers. If signs are to be efficient and successful at encouraging proper and safe behavior and positive attitudes toward automated vehicles, they must convey an appropriate level of detail in a manner comprehensible to unfamiliar drivers.

METHOD

The following section describes data collection methods and the experiment administered to participants.

Apparatus

The researchers conducted the study using the Sign Lab in the Human Factors Laboratory located at TFHRC. A 60-inch diagonal LED/LCD monitor was used to display the experimental scenarios. Participants responded using a standard QWERTY keyboard and mouse or by telling their responses to a researcher who they observed inputting their responses.

Stimuli

This experiment was designed to discover the minimum amount of information and simplest form of delivery sufficient to support safe driving behavior and reduce negative driver perceptions. The designs for the stimuli tested in the experiment were based on standard signs similar to those used on present-day trucks and roadways. The wording on text-based signs was informed by previous survey results (figure 8).

Truck-mounted signs were visualized as simple, mountable electronic signs that could fit into existing hazard-placard mounts on truck trailers, thus allowing the signs to dynamically reflect the status of the platoon. For comparison, the researchers considered the effects of a light bar mounted on the rear of the truck, similar to those proposed for trucks and used in other research regarding external interfaces for automated vehicles. Roadside-mounted signs were designed as standard roadway warning, notice, or portable changeable message signs (CMS).

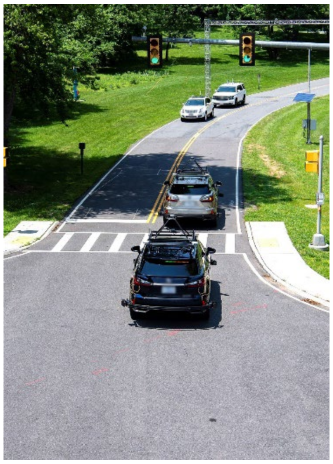
Except for the light-bar design, these sign formats are relatively standardized and are expected to represent manageable effort and production costs. However, real-world implementation must still account for the challenge of implementing signals on exchangeable trailers that may not always remain with the same truck cab. Because the goal of this experiment is to identify valuable types and delivery methods for information related to truck platoons, researchers did not address the potential issue of implementing signals on exchangeable trailers at this stage. If warranted, based on the experimental findings, further testing may be pursued to adapt usable content into a format better suited for real-world truck operations.

Roadside-mounted signs provided general advanced notice that closely grouped, partially automated trucks may be or are currently operating on the roadway. Truck-mounted signs specifically identified equipped trucks as well as their active platooning status.

In addition to viewing traditional sign formats, one group of participants viewed trucks with a static, constantly illuminated light bar mounted near the bottom of the trailer, without any other form of signing in the scenario (figure 9). These light bars reflect designs currently in development and proposed as external human-machine interfaces to notify light-vehicle drivers of the presence or operations of automated vehicles.(Lagström and Lundgren 2015; Benderius, Berger, and Lundgren 2018) Similar devices, which are animated with unique strobing patterns, are currently employed in passenger-vehicle platoons being developed by FHWA (figure 10) (FHWA 2019). These light bars are expected to bring attention to the atypical operation of the vehicles without explicitly identifying them as partially or fully automated or necessarily reflecting their intended maneuvers. The low level of information provided by a generic light bar served as a comparison to the varying levels of specific information provided by truck- and roadside-mounted signs.

Source: FHWA.

Figure 9. Illustration. Simulated light bar used in the current experiment.



Source: FHWA.

Figure 10. Photograph. Strobing light bars on a prototype passenger vehicle platoon.

Design

The researchers assigned participants to one of four experimental groups that each received different experimental stimuli (table 3). All participants viewed control-condition scenarios prior to viewing scenarios that included the experimental stimuli.

Table 3. Sign conditions by experimental group.

Group Number	Roadside-mounted Sign	Truck-mounted Sign
1	R1	T1
2	R2	T2
3	R3	T3
4	None	Light bar

Procedure

Participants viewed static simulated images depicting two heavy trucks with a following-distance gap of approximately 32 ft and were asked to describe their assumptions about the trucks' behavior, their anticipated behavior around the trucks, and their judgments of the trucks' safety and operational independence. Participants first viewed and answered questions for the set of images that did not contain experimental signs or markings (control condition). Then, participants observed the same set of images with the addition of one or two novel signs and answered the same questions shown earlier (table 4).

Table 4. List of questions.

Question Text	Image Reference	Response Options
Imagine that the vehicles are traveling at 55 mph. Which would you be most likely to do to enter the highway (choose one)?	Figure 11-B	Speed up and merge ahead of the front truck. Merge between the two trucks.

Question Text	Image Reference	Response Options
		Slow down and merge behind the closer truck.
Please explain why you chose your previous response.	Figure 11-B	Free response.
How do you think the trucks would respond if you attempted to merge in between them?	Figure 11-B	Free response.
What would you do if you came across this vehicle on the highway?	Figure 11-C	Free response.
Imagine that the vehicle is traveling at 55 mph, and you need to take the Main Street exit. Which would you be most likely to do (choose one)?*	Figure 11-C	Move to the left lane and continue at your current speed. Stay in the right lane and continue at your current speed. Stay in the right lane and slow down. Move to the left lane, speed up, and pass the truck.
Please explain why you chose your previous response.	Figure 11-C	Free response.
If Truck B changed lanes to the left, how do you think Truck A would most likely respond?	Figure 11-D	Truck A would continue in its current lane. Truck A would change lanes behind Truck B. Truck A would remain in its current lane, speed up, and pass Truck B.
How safe do you think these trucks are?	Figure 11-D	1=Very unsafe; 5 =Very safe.
How safe would you feel driving near these trucks?	Figure 11-D	1 = Very unsafe; 5 = Very safe.
Compared to typical distances between trucks, how would you describe the distance between the trucks in the image?	Figure 11-D	1 = Much shorter than average; 5 = Much longer than average.
How do you think the trucks are operating?	Figure 11-D	As two independent, single trucks. As one cooperative unit.
Please explain why you chose your previous response.	Figure 11-D	Free response.

*1-mi exit; repeated for half-mile exit.

At the start of each set of questions, participants were instructed to imagine that they were driving along the highway at the posted speed limit of 55 mph. Scenario images were then shown following the sequence in figure 11. For scenarios in which the truck had a sign attached, a larger version of the sign was shown to the right side of the scenario for easy viewing.

Control-condition scenarios appeared the same as those in figure 11 but without the additional sign.

Source: FHWA.

A. Beginning of entrance ramp.

Source: FHWA.

C. Approaching an assigned exit

Source: FHWA.

B. Merging onto the highway.

Source: FHWA.

D. Wide side view with trucks labeled.

Figure 11. Illustrations. Progression of experimental scenarios. (Roldan and Gonzalez 2021)

After participants completed all questions related to experimental scenarios, the researchers assessed the legibility distance (the maximum distance at which the participant could read text or decipher the elements of the sign). Each sign appeared singly on a black background. The sign presentation began at a simulated distance of 600 ft. The sign then expanded in size to simulate an approach speed of 55 mph. Figure 12 represents this process.

Source: FHWA.

Figure 12. Illustration. Progressive enlargement of signs during legibility testing.

Participants were instructed to watch the sign and then press a key on the keyboard when the sign became legible (i.e., as soon as they could identify the elements of the sign). When the participant pressed the button, the sign disappeared, and the simulated distance was recorded. The participant was then asked to describe the sign aloud. If the description was accurate, the researcher began a new trial with a different sign. If the response was inaccurate, the same sign displayed again from the distance at which it was last seen and continued to increase in size to allow the participant another opportunity to press the button when the sign became legible. Criteria for accuracy considered the sign's intended meaning and distinct elements of its design configuration.

Next, participants ranked sign options for perceived effectiveness and personal preference. In the ranking section, participants were given a description of the intended meaning of each sign category aligned with the selected use case and sign goals. Participants were shown all sign alternatives for a given category and asked to rank each sign alternative based on its perceived effectiveness at conveying the intended message and then rank signs based on their personal preference. Finally, after receiving a brief description of partially automated truck platooning technology and operations, participants were asked to share their opinions on effective methods of signing truck platoons. After completing these questions, participants were debriefed and paid.

Participants

The participants comprised 48 licensed drivers from the Washington, DC, metro area. Participants were evenly distributed across gender (male, female) and older than 46 yr or younger than or equal to 46 yr. Participant's ages ranged from 19–76 yr, with a mean age of 44.8. Participants completed a vision screening to ensure 20/40 vision in one eye or better, as required to become a licensed driver in most States. Two participants reported previous experience as a truck driver or with experience driving heavy vehicles such as freight trucks. One person stated an approximately 1.5-yr tenure with the military, and the other reported a 3-yr tenure as a truck driver. Because responses from these participants were generally neutral to positive and did not appear to meaningfully vary from the rest of the sample, these responses were retained and analyzed along with the rest of the dataset.

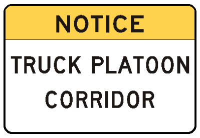
ANALYSIS RESULTS

For this study, the researchers analyzed responses to control scenarios in which novel signs did not appear on the roadside or trucks as baseline responses and compared the baseline to responses provided for scenarios, including novel sign stimuli. Data were analyzed using generalized linear or logistic regression models, as specified in the following sections.

Sign Meaning

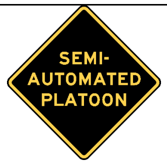
Participants were asked to describe their understanding of novel signs with the question, “What is the meaning of the sign [light bar]?” Open-ended responses were coded for accuracy according to whether the response indicated an understanding of some or all of the following features of the trucks depicted in the scenario: they are traveling as a group/following one another; they are using wireless communication and/or connected technology; they are operating with some type of automated vehicle function(s); they are maintaining close following distances, and/or cut-ins from other vehicles are discouraged. In addition, sign meaning responses that fell into general categories such as caution/warning, multiple trucks on roadway, unspecified truck braking, and unsure responses were coded in separate categories. The proportion of responses within each category for each type of sign are shown in table 5 and table 6.

Table 5. Percentage of responses regarding the meaning of roadside-mounted signs grouped by message category.

Response Category	 **R1***	 **R2**	 **R3**
Group/following	25	67	58
Communication/connected	38	0	8
Automated	0	8	0
Close distance	13	17	8
Avoid cut-in	0	0	8
Warning	0	8	0
High truck volume	0	0	25
Unsure/don’t know	25	8	25
Other/incorrect	13	25	8

All images source: FHWA.
*$N = 8$.

Table 6. Percentage of responses regarding the meaning of truck-mounted signs grouped by message category.

Response Category	 T1	 T2	 T3	 Light bar
Group/following	33	83	42	17
Communication/connected	50	8	42	17
Automated	33	0	42	8
Close distance	8	17	0	0
Avoid cut-in	8	8	8	0
Warning	0	0	0	42
Braking	0	0	0	17
Unsure/don't know	17	8	25	25
Other/incorrect	33	17	17	8

All images source: FHWA.

Interpretations of sign meaning varied slightly across stimuli. Among roadside-mounted signs, sign R1 had the highest comprehension for communication/connected technology (38 percent), sign R2 was highest for group/following (67 percent), automated operations (8 percent), and close distance following (17 percent), and sign R3 was highest for group/following (58 percent) and avoiding cut-ins (8 percent). Notably, sign R2 also had the lowest rate of unsure responses among roadside-mounted signs (8 percent versus 25 percent for signs R1 and R3). However, other/incorrect responses for sign R2 reached a rate of 25 percent.

Comprehension for truck-mounted signs was slightly more varied; light bars were associated most often with general warnings or unclear meanings, with an average of approximately 8 percent of responses reflecting any of the characteristics distinctive of a partially automated truck platoon. Among remaining truck-mounted signs, sign T2 had the highest comprehension for group/following (83 percent) and close distance following (17 percent), sign T1 had the highest comprehension for communication/connected technology (50 percent), and sign T3 had the highest comprehension for automated operations (42 percent). All three text/symbol signs had an equivalent level of comprehension for avoiding cut-ins (8 percent).

Merging

Merge Choice. In the first experimental scenario, participants were asked to describe what they would do to merge onto the highway with a truck platoon in the adjacent lane. In the control condition, 1 participant (2 percent) reported that they would speed up and merge ahead of the front truck, 1 participant (2 percent) said they would merge between the two trucks, and 46 participants (96 percent) stated they would slow down and merge behind the closer truck (table 7). When asked to explain their answer, nearly all participants noted a desire to maintain safety or avoid a collision with the trucks. Notably, 10 percent of participants mentioned not wanting to get sandwiched or stuck between the trucks or generally wanted to give them space.

Table 7. Percent of responses to the question, "Which would you be most likely to do to enter the highway?"

Group	Condition	Speed up and merge ahead of the front truck	Merge between the two trucks	Slow down and merge behind the closer truck
All	Control	2	2	96
1	R1-T1	0	0	100
2	R2-T2	0	0	100
3	R3-T3	0	0	100
4	None-Light bar	0	8	92

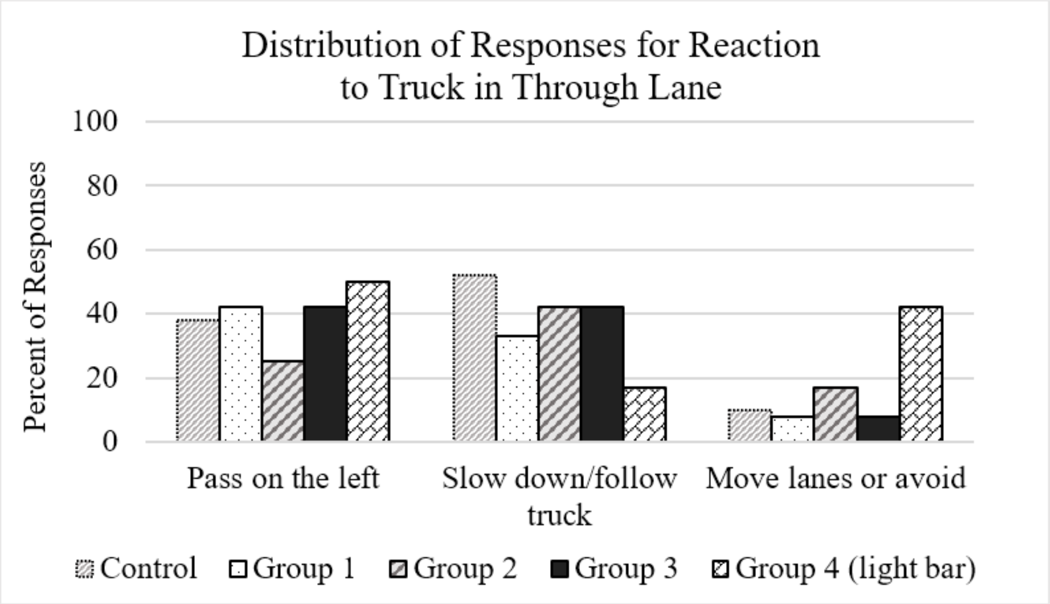
When participants in the light bar condition (Group 4) were asked to explain their choice, the small space in which to merge remained a commonly cited reason to avoid cutting in (33 percent). Of these participants, 1 (8 percent) reported that they would merge between the trucks, and 11 (92 percent) would choose to slow down and merge behind the closer truck. The option to speed up and merge ahead of the front truck was never chosen. For the remaining sign combinations (Groups 1–3; Table 7), all participants (100 percent) chose to slow down and merge behind the closer truck.

Forced Merge. When participants were asked to anticipate the reaction of the trucks during an attempt to merge between them, most participants in the control condition expected a negative reaction, with 56 percent of responses expecting the trucks to perform risky maneuvers, such as sudden acceleration or deceleration, swerving, veering, or colliding with another vehicle. Some participants also expected truck drivers to respond unfavorably to an attempted merge; 38 percent of responses anticipated honking, flashing headlights, or general aggression from the truck drivers.

Participant responses for trucks with light bars or signing were similar to those for unsigned trucks. In the light bar condition, 50 percent of participants predicted general truck aggression or honking, 33 percent expected trucks slowing down or possibly colliding, and 17 percent mentioned automated or communication devices in the trucks. An equal number of participants (8 percent) expected to be allowed to merge or be prevented from merging. In signed truck conditions, 50 percent of participants expected one or more trucks to brake, slow down, or possibly collide with another vehicle; 25 percent anticipated aggression such as honking horns or flashing lights; 11 percent thought the trucks would try to prevent the merge, and 14 percent thought the trucks would allow the merge. Unlike in the control condition, 11 percent of responses in signed scenarios mentioned automation or communication between the vehicles as a factor in the anticipated truck response.

Through Travel

Next, participants viewed an image depicting the driver in the same lane behind the rear truck. Participants were asked, "What would you do if you came across this vehicle on the highway?" with no explicit indication given that the driver was expected to exit the highway at this time. Free responses were categorized by three major behaviors: passing on the left, changing lanes or otherwise avoiding the truck, or slowing down or following the truck (figure 13). Because some responses mentioned multiple behaviors, responses may have been grouped into more than one category, thus resulting in total percentages above 100 within a group condition.



Source: FHWA.

Figure 13. Graph. Percent of responses to the question "What would you do if you came across this vehicle on the highway?"

In the control condition, 38 percent of responses indicated that participants would attempt to pass the truck on the left; 52 percent stated participants would slow down and follow behind the truck, and 10 percent stated they would move lanes to the left or otherwise avoid driving behind the truck. Several participants mentioned the influence of the truck's speed on their decision, indicating they would be more likely to attempt to pass on the left if the truck was traveling slower than the speed limit.

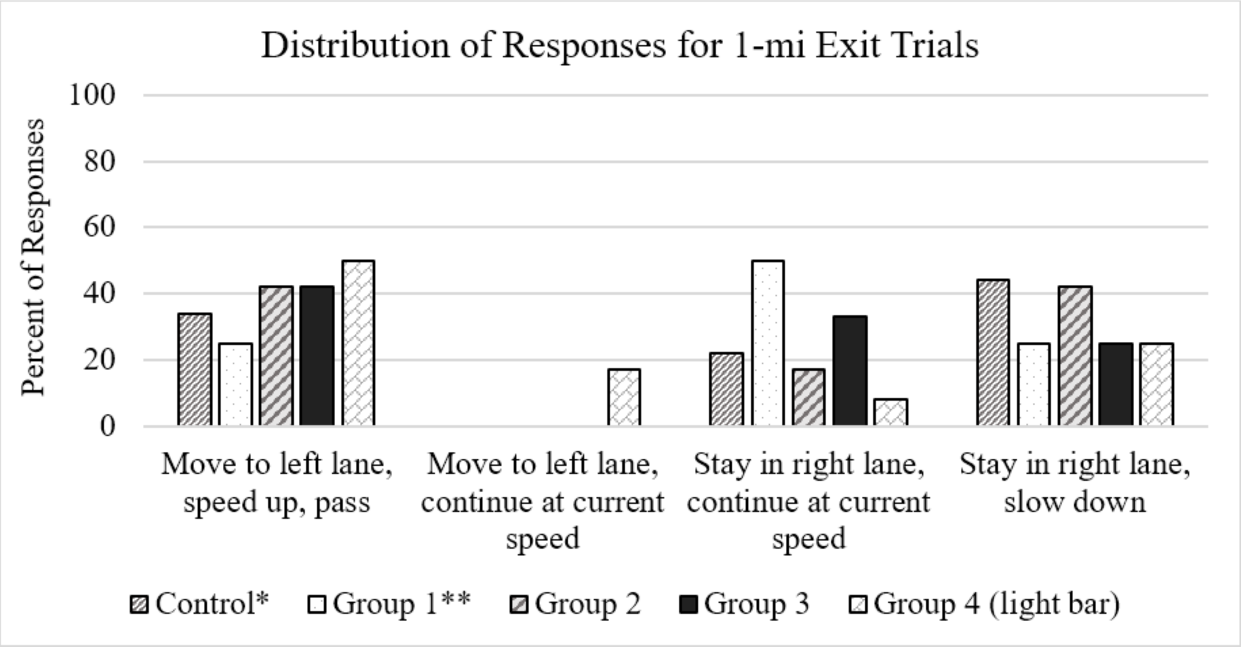
In the light bar condition, 50 percent of participants said they would attempt to pass the truck; 17 percent would slow down or follow behind the truck, and 42 percent would change lanes or otherwise distance themselves from the truck. In general, the light bar appeared to motivate participants to stay away from the platoon by passing or changing lanes more so than any other condition.

Responses to the three signed conditions were similar overall, with a mean of 36 percent of participants who would pass the truck, 39 percent who would slow down or follow the truck ahead of them, and 11 percent who would change lanes or otherwise keep their distance from the truck. Notably, two participants (5 percent) mentioned the possibility of another truck ahead of the one they could see; both responses were from Group 2 participants, who saw sign T2. Group 2 was also associated with a lower rate of passing responses (25 percent) compared to the other signed groups (Groups 1 and 3; 42 percent each), the light bar group (50 percent), and the control condition (38 percent). Compared to the control condition, a slight decrease occurred in the proportion of responses related to slowing down or following the trucks.

Exiting

One Mile. Participants were asked to select a likely response when approaching a desired exit behind a platooning truck. In this scenario, the sign indicated that the exit was 1 mi ahead on the right. In the control condition, more participants (44 percent) chose the option to "stay in the right lane and slow down," followed by "move to the left lane, speed up, and pass the truck" at 34 percent and "stay in the right lane and continue at your current speed" at 22 percent. A portion of participants (38 percent) explained their response as a desire to avoid missing the exit or thought that the distance to the exit 1 mi away would be too short to warrant or risk passing the truck. In addition, 28 percent of responses mentioned concerns about the driver's visibility of the road ahead or of the truck driver's visibility of the passing vehicle.

"Move to the left lane, speed up, and pass the truck" was the most frequently chosen response for the light bar (50 percent) and Group 3 (42 percent) conditions. However, for Group 2, the top two responses were to "stay in the right lane and slow down" and "move to the left lane, speed up, and pass the truck," at 42 percent each. For Group 1, the option to "stay in the right lane and continue at your current speed" was the most frequently chosen, at 50 percent. A summary of response selection is provided in figure 14.



Source: FHWA.

*N = 32; **N = 8

Figure 14. Graph. Percent of responses selected for reaching an exit 1 mi ahead based on condition.

When light-bar and sign-condition responses were compared to control responses for the 1-mi exit scenario, the researchers noted that 25 percent of participants changed their response. Of these, 38 percent of participants changed from a more aggressive response to a less aggressive one, 38 percent switched from less aggressive to more aggressive, and 25 percent chose a similar response (e.g., “staying in the right lane and slowing down” and “staying in the right lane and continuing at current speed”).

Statistical analysis performed using a generalized logit model with a multinomial nominal distribution (Agresti 2007) showed insufficient evidence to conclude that either gender or age group were significantly related to response choices in the control condition. Similarly, no statistical evidence was found of a relationship between response choice and sign condition, gender, or age group. The comparison between responses to control and light-bar or sign-condition scenarios revealed no significant statistical differences. In addition, the likelihood of participants changing a response was not significantly different between the light bar and other sign conditions.

Half Mile. Participants then viewed the same scenario including a sign stating that the exit was one-half mi ahead rather than 1 mi. Response selection remained similar to those in the 1-mi scenario, with a greater distribution of choices involving staying in the right lane.

Nearly half of participants in the control condition explained their choice by stating that the exit was too close to risk or warrant maneuvering around the truck (47 percent). In the light bar condition, one participant stated that they wanted to avoid staying behind the truck because they assumed it was “engaging with another related vehicle” and wanted to allow space for it to maneuver. Most participants in the signed conditions cited the distance to the exit (41 percent) or safety (22 percent) as the reason for selecting their response. An additional 13 percent of participants were concerned with visibility around the truck, and 13 percent specifically mentioned the possibility of additional trucks ahead of the visible truck in front.

Of the 32 valid responses collected, 31 percent changed their response between the half-mile control and light-bar or signed scenarios. Of these, 60 percent of participants switched from a more aggressive response to a less aggressive one, 30 percent switched to a more aggressive response, and 10 percent chose a similar response to the one selected in the control condition. Once again, no evidence existed for a statistically significant relationship between control or sign conditions, gender, or age group with any of the response categories. The distribution of responses was not significantly different between the light bar and other sign conditions.

One Mile and Half Mile Comparison. Between the control condition 1-mi and 1/2-mi exit scenarios, 32 percent of participants changed their response. Among trials containing a light bar or sign, 44 percent of responses were different between the 1-mi and 1/2-mi exit scenarios, with the highest rate of change in Group 3 (58 percent). A logit binomial model revealed a significant effect of gender on the odds of changing response selection between the 1-mi and 1/2-mi scenarios, $\chi^2(1) = 4.52$, $p = .0336$, such that odds of females changing their response was 3.99 times greater than those of males. Sign condition and age group were not found to have an effect, and their interactions were not explored.

Truck Predictability

The next question asked participants to anticipate the maneuvers of the platooning trucks. In this question, option 2 was the response indicating an understanding that trucks were intentionally and continuously traveling together, “Truck A would change lanes behind Truck B.” When participants were asked how they expected the following truck to respond to the lead truck moving over to the left lane, the majority of participants (71 percent) in the control condition chose option 1, “Truck A would continue in its current lane.” However, when a sign or light bar was present, option 2 was the most frequently chosen response (66–83 percent).

Data were analyzed using a generalized logit link model with a multinomial distribution. The difference in option choice between control and light bar or signed conditions was significant, $\chi^2(2) = 29.97$, $p < .0001$. Both age group, $\chi^2(1) = 4.07$, $p = .0436$, and gender, $\chi^2(1) = 7.00$, $p = .0082$, were significantly related to the odds of changing a response from option 1 in the control scenario to option 2 in the signed scenario, such that the odds of females changing their response was estimated to be 6.32 times higher than those of males, and the younger age group was 4.27 times more likely than the older age group to change their response. Neither age group nor gender were significantly associated with the likelihood of response choice in the control condition. Likewise, condition, age group, and gender were not found to have a significant relationship with response choice in light bar or sign condition.

Safety

Participants rated their perceptions of the safety of the trucks as well as their own sense of personal safety if driving near them on a scale of 1 = very unsafe to 5 = very safe. Responses were analyzed using a GEE model with a normal distribution and Tukey-Kramer correction for pairwise multiple comparisons. Compared to control scenarios (2.60 mean rating), truck safety was significantly higher for scenarios that included signs (2.98 mean rating), $\chi^2(1) = 4.69$, $p = .0303$. Similarly, personal safety ratings were significantly higher in signed (2.88 mean rating) compared to control (2.40 mean rating) scenarios, $\chi^2(1) = 7.84$, $p = .0051$.

An analysis of the influence of condition type, gender, and age group on safety ratings revealed an interaction between sign condition and gender on truck safety ratings, $\chi^2(3) = 8.56$, $p = .0357$, such that males in Group 2 (3.50 mean rating) provided significantly higher safety ratings than those in Group 4 (3.33 mean rating), Group 1 (2.67 mean rating), and Group 3 (2.17 mean rating). Among sign conditions, no significant main effects or interactions with condition, gender, or age group were found.

Truck Operations

The final experimental question directly asked participants to decide whether they expected the trucks to be operating as two single, independent units or as one cooperative unit. A GEE with a binomial distribution was used to explore significant effects of condition, gender, and age group on responses. Trucks in control scenarios were rated as independent in 58 percent of responses. In contrast, trucks with light bars were judged to be independent in 8 percent of responses, and signed trucks were rated as independent in an average of 16 percent of responses. The likelihood of choosing the cooperative response option was significantly higher in sign/light bar scenarios compared to control scenarios, $\chi^2(4) = 19.83$, $p = .0005$, and responses were not significantly associated with age group or gender. Although the ratio of cooperative responses was slightly lower for Group 2 compared to the other signed scenarios, the analysis revealed no significant differences in the likelihood of choosing the cooperative response option among sign conditions.

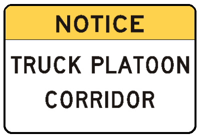
When explaining their response choice, the majority of participants referenced the general appearance of the trucks, distance between them, and the signing (when present) in their judgement of whether the trucks were operating independently or cooperatively. In the control scenario, 27 percent of responses noted general truck appearance as an explanation, and 21 percent mentioned truck-gap distance. In the light-bar condition, 50 percent of responses mentioned the light-bar indicator, 42 percent mentioned general truck appearance, and 17 percent noted truck-gap distance. In signed scenarios, 75 percent of responses mentioned the sign, 14 percent mentioned general truck appearance, and 19 percent mentioned truck-gap distance.

In the control condition, many participants who thought the trucks were operating independently explained that they had no previous exposure to trucks driving cooperatively; participants would assume trucks without a physical connection to be independent.

Legibility

The ability to read and comprehend a sign from afar can facilitate early behavioral planning. Legibility data were averaged to identify signs with greater legibility distances. In a few cases, participants gave a response after the sign had reached its specified maximum viewing size, resulting in negative legibility values. To improve interpretability, these values were floored to 0, indicating a legibility of 0 ft away from the sign. Two participants were unable to accurately describe one of the signs before it reached its maximum presentation size. These instances were removed from the dataset. A summary of legibility scores for each sign is provided in table 8 and table 9.

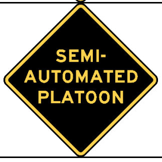
Table 8. Mean legibility distances for roadside-mounted signs.

Sign Image	Sign ID	Mean Legibility Distance (ft)	Mean Standard Deviation (ft)
	R2	252.2	38.00
	R3	205.6	74.28
	R1	158.9	45.40

All images source: FHWA.

Note: Signs are listed in order of highest to lowest legibility distance.

Table 9. Mean legibility distances for truck-mounted signs.

Sign Image	Sign ID	Mean Legibility Distance (ft)	Mean Standard Deviation (ft)
	T2	174.3	31.20
	T1	170.1	47.34
	T3	157.1	50.30

All images source: FHWA.

Note: Signs listed in order of most effective to least effective.

The researchers analyzed legibility data using a GEE model with a normal distribution, which accounted for repeated measures. Sign, gender, age group, and participant interactions were explored. A Tukey-Kramer multiple comparison correction was applied when exploring pairwise comparisons for significant effects. Roadside-mounted signs and truck-mounted signs were analyzed together as well as separately.

Among the comparisons of all sign conditions and including all variables and interactions, legibility distance varied significantly across signs, $\chi2(5) = 465.08$, $p < .001$, with sign R2 having the greatest legibility distance at 252.2 ft. Sign R3 (205.6 ft) was also legible at a significantly greater distance than that of the remaining signs. Sign T2 (174.3 ft) was significantly more legible than signs R1 (158.9 ft) and T3 (157.1 ft).

Among roadside-mounted sign comparisons, a significant effect of age group was noted for sign R2, $\chi2(1) = 8.06$, $p = .045$, such that legibility distances for participants less than 46 years old were, on average, 28.94 ft greater than those of participants aged 46 or older. No other significant interactions with age group were found for the remaining roadside-mounted signs.

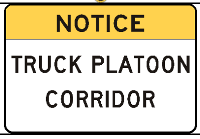
Among the comparisons for truck-mounted signs, the legibility distance for sign T2 (174.3 ft) was significantly greater than that of sign T3 (157.1 ft). However, the difference in legibility distances for signs T1 and T2 (170.1 ft) was not significant. No interactions with age group were found for truck-mounted signs.

Ranking

In the next section of the experiment, participants were shown all the possible sign stimuli and rated them based on perceived effectiveness and personal preference. Roadside-mounted and truck-mounted signs were scored separately. Data were analyzed using a normal distribution, and a Tukey-Kramer multiple comparison correction for pairwise comparisons was applied. Roadside-mounted and truck-mounted signs were analyzed separately.

Table 10 and table 11 provide the mean rating scores for signs, with scores closer to 1 indicating greater effectiveness or personal preference. For roadside-mounted signs, sign R2 was ranked as most effective (1.54) and most preferred (1.69). On average, participants ranked sign T2 as the most effective (1.69) and most preferred (1.81) truck-mounted sign. The truck-mounted light bar (3.06) and roadside-mounted sign R3 (2.44) were ranked as least effective, although the light bar was not the least preferred of the truck-mounted signs. The difference in effectiveness rankings was significant for roadside-mounted, $\chi^2(2) = 27.08$, $p < .0001$, and truck-mounted signs, $\chi^2(3) = 25.99$, $p < .0001$. Similarly, preference rankings varied significantly across roadside-mounted, $\chi^2(2) = 20.04$, $p < .0001$, and truck-mounted signs, $\chi^2(3) = 37.70$, $p < .0001$.

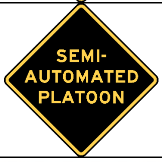
Table 10. Mean ranking scores for roadside-mounted signs.

Sign Image	Sign ID	Mean Effectiveness Ranking	Mean Preference Ranking
	R2	1.54	1.69
	R1	2.02	1.88
	R3	2.44	2.44

All images source: FHWA.

Note: Signs listed in order of most effective to least effective.

Table 11. Mean ranking scores for truck-mounted signs.

Sign Image	Sign ID	Mean Effectiveness Ranking	Mean Preference Ranking
	T2	1.69	1.81
	T1	2.52	2.40
	T3	2.73	3.04
	Light bar	3.06	2.75

All images source: FHWA.

Note: Signs listed in order of most effective to least effective.

Age group had a significant effect on effectiveness for roadside-mounted signs, $\chi^2(2) = 13.27$, $p = .0013$. The order of most to least effective signs as ranked by older participants was sign R2, followed by signs R3 and R1, whereas younger participants ranked sign R2 as most effective, followed by signs R1 and R3. Although the order of ranked effectiveness varied, sign R2 remained the most effective sign for both age groups.

Relative preference rankings were similar to those of effectiveness, with signs T2 and R2 as the most preferred. Once again, preference for roadside-mounted signs varied according to age group, $\chi^2(2) = 17.92$, $p = .0001$. However, unlike roadside signs, the most preferred sign varied between age groups. Older participants preferred sign R2 most, followed by signs R3 and R2. However, younger participants preferred sign R1 most, followed by signs R2 and R3.

Post-Test Questions

After completing the main portion of the experiment, participants were asked their opinions on the usefulness of including signs to notify drivers of truck platoons. Participants were provided a brief description of truck platoons and their operations to aid their understanding. When asked whether they thought signs on the truck, signs on the entrance ramp/along the roadway, a combination, or no signs were best for notifying drivers, most participants (83 percent) were in favor of a combination of signs, whereas 17 percent were in favor of signs on the truck only. No other response options were chosen.

When participants were asked to rate the effectiveness of the combination of truck and road signs viewed during the experiment on a scale of 1 (very ineffective) to 5 (very effective), the mean response was 3.92, suggesting that the sign stimuli were moderately effective. The combination used in Group 2 (signs R2 and T2) was rated as most effective on average (4.18), followed closely by Group 1, consisting of signs R1 and T1 (3.92). However, the difference in ratings was not statistically significant, and no significant effects of gender or age group were identified.

DISCUSSION

In this experiment, drivers viewed scenarios in which two simulated trucks appeared on a two-lane highway with a short following gap of approximately 32 ft (0.4 s at 55 mph). Participants viewed trucks in a variety of travel scenarios and reported on their likely behavior and subjective experience. The same scenarios were then presented with one of four sets of roadside-mounted signs and truck-mounted signs or indicators designed to reflect the partially automated, connected nature of the trucks' operations. Participant responses were explored for the effects of sign treatments on their navigational choices, safety-related behavior around the trucks, and their understanding and perceptions of the trucks' behavior.

The results of the experiment showed that drivers' understanding of truck platoons varied with the presence and type of sign or indicators presented. Among roadside-mounted signs, sign R2 had the highest rate of comprehension within a single category, with over half of responses indicating that the trucks were in a group or following one another. Sign R1 facilitated a broader array of understanding, with participants describing group/following behavior as well as communication or connected technology and close-distance following. Sign R3 also elicited high rates of group/following responses but relatively lower rates within the other behavioral categories; this sign was also more frequently associated with high truck volumes, which may or may not be accurate for roads occupied by truck platoons but is not related to the intended meaning of the sign.

Among truck-mounted signs, the light bar was least successful at conveying the intended behavioral categories. Instead, the light bar was seen to indicate general warning, truck braking behavior, or was unable to be interpreted. This suggests that an ambiguous, steady-state light indicator, while potentially attention-capturing, is likely to be too vague to support desired understanding of—and subsequent behavior around—partially automated platoons. Although animated patterns such as those explored in previous research may provide a clearer message regarding the platoon's activities, previous research also supports the combination of amber and blue lights as a warning signal to encourage driver braking. (Andersson and Voronov 2017; Ullman 2000)

In comparison to the light bar, signs T1, T2, and T3 performed more efficiently, each reflecting at least four of the five behavioral categories. Sign T3 consistently elicited a moderate understanding of group/following behavior, communication/connected technology, and automation. However, a quarter of responses for sign T3 indicated participants' uncertainty about the meaning of the sign. Sign T1 reflected all five message categories, with the highest rate of responses reflecting communication/connected technology. Sign T2, on the other hand, had the highest rate of comprehension for group/following behavior as well as close-distance following. All three signs had an equally low rate of responses regarding avoiding cut-ins.

When evaluating the most important messages to convey to light-vehicle drivers near truck platoons, the grouping and close-distance following are arguably the most actionable and immediately relatable characteristics for nearby drivers. Even if drivers do not have a strong understanding of automated or connected vehicle technology, knowing that the trucks are expected to stay in a group and follow each other closely should be sufficient to encourage light-vehicle drivers to give the trucks ample space to maneuver together. Close-distance following should also indicate to the driver that safely merging in between the trucks might be difficult.

The results of the experiment provide evidence that signs or indicators influenced drivers' perceptions of the trucks' operations and the relationship between them. Although the mere appearance of the simulated trucks may be sufficient to suggest close-distance following, the researchers observed that short gap distances did not necessarily imply intentional following. In the control condition, less than 20 percent of participants expected the unsigned trucks to execute lane change maneuvers in tandem. However, this pattern reversed when a sign or indicator was present on the truck; over 60 percent of participants within each group expected the rear truck to follow the lead truck into the left lane. In addition, operational and personal safety ratings were consistently lower for unsigned trucks compared to trucks presented with a light bar or sign. In fact, the highest ratings of personal and truck safety were associated with Group 2 (signs R2 and T2).

Interestingly, although most participants in Group 2 (just below 80 percent) expected the trucks to follow one another, the proportion of responses indicating that the trucks were operating cooperatively was the lowest for Group 2 out of the four sign combinations (though still substantially higher than that of the control group). This fact may indicate some discrepancy between the understanding that vehicles are merely traveling in a group as opposed to intentionally traveling cooperatively to coordinate their movements. The relatively low proportion of responses that associated sign R2 with automated technology may indicate that the sign led drivers to conceptualize a platoon operated and controlled by human drivers rather than one monitored and supervised by an automated vehicle system. As a result, a platooning operation that relies on truck drivers actively choosing to participate and comply may appear transient or volatile to light-vehicle drivers.

When asked how they would likely enter the highway with a truck platoon in the adjacent lane, nearly all participants stated that they would choose to drop back behind the following truck to merge onto the highway. These responses did not appear to be significantly related to the sign condition used. Participants' explanations suggested that merge decisions were often attributable to the small gap between the trucks. Note that the gap size depicted in the simulated scenario was substantially smaller than the gaps shown to be minimally acceptable for cut-ins in real-world scenarios, which may have affected participants' responses. (Nodine et al. 2017). However, some participants did appear to interpret signs and indicators as signals to avoid interrupting the trucks because the trucks were traveling together as a group. Across all sign conditions, an average of 32 percent of participants expressed a desire to avoid cutting in between the trucks. In particular, Group 2 (signs R2 and T2) had a high rate of responses indicating that the trucks were traveling together (67 percent) and that drivers would avoid cutting in between the trucks (55 percent).

Although merging behind the platoon is favorable for safety, this behavior could lead to reduced traffic flow and throughput benefits expected to result from truck-platoon deployment. Traffic simulations found that, at high market penetration of truck platoons, merges onto the highway failed more frequently and shifted toward the end of the acceleration lane during congested conditions (Wang, Happee, Tool, and van Arem 2019) An evaluation of three different mitigation strategies, including courtesy lane changes by the platoon, active yielding to merging vehicles, and maintaining wider intra-platoon gaps, showed that yielding by the platoon was most effective for solving the merge problem in congested traffic. This strategy, however, required the platoon to temporarily dissolve to allow a merge, and benefits were only observed at high market penetration rates of 75 or 100 percent and during congested traffic conditions. In contrast, applying this strategy at low market penetration (25 percent) and during free-flow traffic did not produce significant benefits. The simulation findings suggest that additional changes to the platoon's behavior may not be necessary to prevent negative effects on traffic flow and throughput at merge points during early deployment.

This experiment showed that signing did not appear to meaningfully influence drivers' expectations of how trucks would react to an attempted cut-in. The mean frequency of anticipated collisions or risky maneuvers in signed truck conditions (50 percent) was very similar to that of unsigned trucks in the control condition (56 percent). This result indicates that drivers did not expect signed trucks, which may be equipped with partially automated and connected vehicle technology, to be substantially more robust against collisions or dangerous maneuvers than typical manually driven trucks. However, expectations for general truck driver aggression were slightly lower for signed trucks (25 percent) compared to unsigned trucks (38 percent). Furthermore, trucks with light bars were expected to slow down suddenly or collide in only 33 percent of responses. These reports may suggest that light-vehicle drivers are inclined to expect drivers of partially automated trucks to respond to the behavior of other vehicles in a manner similar to manually driven trucks.

When planning to exit the highway, participants most often chose to remain in the right lane and wait for an upcoming exit, regardless of whether they were 1 mile or 1/2 mi from the assigned exit point. The relatively short distances to the assigned exit and the limited field of view provided in the static scenario image likely influenced these responses. In explaining their decisions to pass or remain in the right lane, several participants expressed concern about maintaining visibility around the truck ahead of them and avoiding entering the truck's blind spot. Signing had a moderate but not statistically significant effect on the likelihood of changing an exit strategy response to a response that involved remaining in the right lane. Regardless of sign treatment, the general trend of response choice shifted toward remaining in the right lane and slowing down at the 1/2-mi advanced sign compared to the 1-mi sign. Females were found to be more likely to change their response at the 1/2-mile marker compared to males, although similar patterns of behavioral differences associated with gender have been identified previously and are not considered meaningful for the evaluation employed in this experiment. (Özkan and Lajunen 2006)

Finally, in through-travel scenarios, participants from Group 2 were most likely to mention the possibility of additional trucks ahead of the one directly in front of them. This awareness may have important implications for early driver planning and navigation. As illustrated by the control condition, participants are likely to attempt to pass a truck on the left under typical conditions. However, when drivers account for the possibility that several unseen trucks with small following gaps are ahead on the roadway, drivers may make safer and more efficient decisions about whether and when to pass the platoon.

The behavioral portion of the experiment required participants to react to a variety of signs and indicators. On a more basic design level, all signs used in the experiment performed well on legibility, with mean legibility distances over 150 ft for all the sign stimuli. A subjective evaluation of the perceived efficacy and preference for the novel sign options revealed signs R2 and T2 as most effective and most preferred. In addition, the majority of participants were in favor of employing a combination of road- and truck-mounted signs to notify drivers of partially automated truck platoon operations.

Based on overall behavioral responses, perceptual performance, and subjective rankings, the authors recommend signs R2 and T2 for further testing. Notably, this combination contains two dynamic signs that could reflect the status of an active platoon in real time. The phrase “linked convoy” used in the signs appears to have improved participants’ comprehension of the grouped and following nature of the truck platoon.

CHAPTER 5. DRIVING SIMULATOR STUDY 1—EFFECTS OF TRUCK PLATOON SIGNING ON LIGHT-VEHICLE DRIVER BEHAVIOR

Previous studies, including a feedback survey as described in chapter 3, suggest that knowledge of automated technology in trucks may influence drivers' decisionmaking when interacting with these vehicles. A behavioral study presented in chapter 4 explored several options for identifying platooning activities and partially automated trucks. This study provided recommendations of roadside and truck-mounted signs that could positively influence drivers' understanding of trucks working cooperatively, predictability of trucks' movements, and drivers' judgments of safety. This chapter describes an experiment that further evaluates the recommended signs' ability to inform light-vehicle drivers about partially automated truck platoons to improve roadway safety and support the successful operation of the platoon.

The primary objective of the study is to determine whether and how knowledge of partially automated truck platooning influences light-vehicle drivers' behavior. The three key research questions studied include the following:

1. Do light-vehicle drivers' strategies for entering and exiting the highway vary with the presence of signs related to partially automated truck platoons?
2. Does driving performance on the through lanes differ when light-vehicle drivers are driving near signed or unsigned partially automated truck platoons?
3. Do drivers' perceptions of effort and safety differ when performing certain maneuvers near partially automated truck platoons?

The researchers studied light-vehicle driver behaviors near partially automated platoons in a driving simulator. The signs used in the study were chosen based on the results of a previous behavioral experiment that suggested the signs are comprehensible to naïve drivers and support desired behavior (e.g., reducing the likelihood of cutting in between the platoon, creating improved perceptions of safety, and generating accurate expectations of platoon behavior). The experiment expanded on the previous study by separately measuring the potential benefits of deploying roadside signs, truck-mounted signs, or their combination relative to no additional signing. A postdrive survey was conducted to collect participants' opinions on their perceptions of safety, driving effort required, and thoughts about the gap distance between trucks when driving near truck platoons.

Due to a focus on early deployment, the experiment was designed with the following assumptions in mind:

- Early truck platoons will consist of two trucks equipped with CACC to automate speed control and maintain a following time gap of 0.6 s under normal circumstances.

- Partially automated platoons in mixed traffic will be expected to follow current-day regulations, such as traveling in the right lane and respecting speed limits.

- Platoon operations will be restricted to good weather conditions on highway corridors frequently used for freight transport and with low to moderate light-vehicle traffic.

- Public knowledge of truck platoons will not yet be widespread, so passenger fleet vehicle drivers are likely to be unfamiliar with platooning technology.
- Minimized cut-ins to the platoon will reduce the need to lengthen following gaps, which decreases fuel and environmental benefits and could potentially facilitate additional cut-ins, thus preventing or delaying reinitiating the platoon.
- Unsafe or undesirable light-vehicle driver behaviors include excessive speeding to overtake the platoon, hard acceleration, high steering variability, maintaining headways of less than 0.6 s with truck platoons, and colliding with other vehicles or roadway structures.

METHOD

The following section describes data collection methods and the experiment administered to participants.

Apparatus

The researchers conducted the study using the NADS quarter-cab miniSim in the Human Factors Laboratory located at TFHRC. Participants viewed three 48-inch high-definition screens that displayed the forward roadway, side mirrors, and rearview mirrors, respectively. An additional 12-inch screen displayed dashboard information. The simulator had a fixed base with an automotive steering wheel and column, pedals, and gear selector. A subwoofer beneath the driver's seat generated road feel.

Stimuli

The stimuli (figure 15) chosen for this experiment were informed by 1) the results of the previously conducted survey on perceptions of truck platoons and 2) a behavioral experiment in which participants rated which signs were most effective and most preferred out of three roadside-mounted sign options and four truck-mounted sign options. A series of self-reported questions also revealed that the higher rated signs encouraged drivers to see the trucks as grouped and intentionally following one another at short distance. Drivers also perceived trucks bearing the signs as safer than those with other sign options or without any signs.

Source: FHWA.

Note: The left sign is roadside-mounted, and the right sign is truck-mounted.

Figure 15. Illustrations. Stimuli.

The roadside-mounted sign was a CMS that provided general advanced notice of closely grouped, partially automated trucks operating on the upcoming highway (figure 16). A portable CMS displayed the sign at six predetermined locations prior to the appearance of the upcoming truck platoon. The portable CMS was 11-ft tall and 11-ft wide, excluding the solar panel. The display panel of the roadside-mounted CMS was approximately 5.3-ft tall and 10-ft wide with 1.2-ft-tall lettering.

Source: FHWA.

Figure 16. Illustration. Participants observing the roadside-mounted sign scenario during driving simulator experiment.

The truck-mounted sign, designed as a negative contrast sign that is illuminated when active, appeared on the lower right-hand side of the rear of each platooning truck to identify the equipped trucks and their active platooning status (figure 17). The truck-mounted sign appeared 2-ft square with approximately 4-inch-tall lettering.

Source: FHWA.

Figure 17. Illustration. Participants observing the truck-mounted sign scenario during driving simulator experiment.

Design

Participants were assigned to one of four experimental groups, which determined the type of signing they would observe during driving (table 12).

Table 12. Sign conditions by experimental group.

Group	Platooning Sign Type
1	None
2	Roadside-mounted only (on-ramp)
3	Truck-mounted only
4	Roadside-mounted and truck-mounted

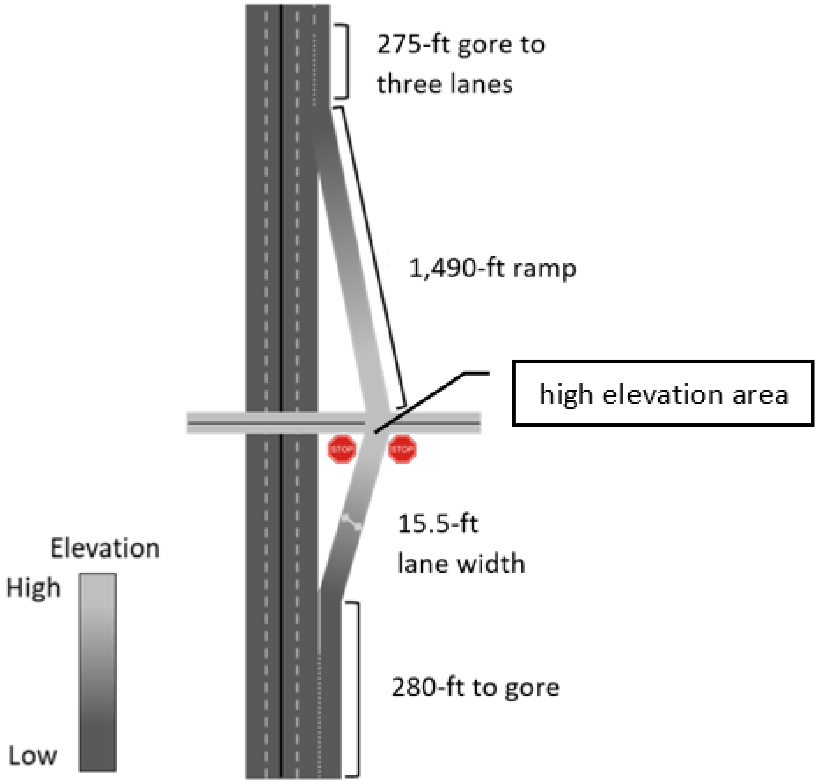
Participants completed a total of 18 trials. On each trial, participants were instructed to either exit and reenter the highway or continue straight. Participants encountered truck platoons at six predetermined intervals, including entering, exiting, and through areas over the trials (table 13). The order and characteristics of trials remained the same for the four groups of participants.

Table 13. Description of trials encountered throughout the Study 1 experimental drive.

Trial	Maneuver	Platoon Present	Platoon Conflict Location
1	Through	No	—
2	Exit/enter	No	—
3	Exit/enter	Yes	Enter
4	Through	No	—
5	Exit/enter	No	—
6	Through	Yes	Through
7	Exit/enter	No	—
8	Through	No	—
9	Exit/enter	Yes	Exit
10	Exit/enter	No	—
11	Through	Yes	Through
12	Exit/enter	No	—
13	Through	No	—
14	Exit/enter	Yes	Exit
15	Through	No	—
16	Exit/enter	No	—
17	Exit/enter	Yes	Enter
18	Through	No	—

— not applicable.

The simulated highway was a four-lane, two-way highway divided by a concrete barrier. The road included merge and exit ramps connected to an overpass (figure 18). Exits occurred every 1.5 mi. For trials incorporating exiting the highway, as participants neared the 1-m advance guide sign for the exit (approximately 4,420 ft from the beginning of the exit lane), a recorded message instructed participants to take the next exit. A reminder navigation message played when the participant was approximately 365 ft from the beginning of the exit lane. Once off the highway, signs directed the participant to come to a stop on the overpass before continuing down the highway entry ramp.



Source: FHWA.

Figure 18. Diagram. Simulated highway ramp.

The partially automated platoon consisted of two standard U.S. tractor-trailer sleeper cabs with approximately 53-ft-long trailers. The total length of the trucks was roughly 70.5 ft from end to end. The trucks had similar—although not overtly identical—markings. The trucks used simulated CACC with speed control to maintain a consistent speed of 55 mph, in adherence to the posted speed limit. The following truck maintained a following-time gap of 0.6 s (48.4 ft) behind the lead truck. To account for realistic fluctuations in time gap due to imperfect vehicle sensors and acceleration systems, the following gap was allowed to randomly vary by ±0.05 s (±4 ft) throughout the drive. The lead truck followed light vehicles at a following gap of 2 s (161.32 ft). If a participant's vehicle merged in between the two trucks, the following truck would adopt a following gap of 2 s.

Collisions (in which the participant's simulated vehicle contacts another simulated vehicle or structure) were recorded but not animated, such that the passenger vehicle driver did not hear or see additional indicators of the collision and could continue driving without interruption. Traffic consisting of light- to medium-weight vehicles and occasional single heavy trucks was present in the participant's lane of travel and at interchanges at designated points. Except for the approach to through event trials, simulated traffic was restricted to the left travel lane. Prior to trials with a platoon on the through lanes, large vehicles (e.g., utility van) might enter the highway ahead of the participant to occlude their view of the traffic ahead. The scenario simulated daytime, clear-weather road conditions.

Procedure

Each session began with participants reviewing and signing the informed consent form. The researchers checked participants' driver's licenses and then assessed participants' vision to ensure a minimum acuity of 20/40 (with correction).

Participants completed a brief 5–10 min practice drive that enabled them to experience what they were about to see and perform in the miniSim driving simulator. Before and after the practice drive, a simulator sickness questionnaire (SSQ) was administered to screen for symptoms of simulator sickness that may have prohibited participants from continuing. Once cleared, participants proceeded with the assigned experimental scenario. The simulated scenario began with the driver at the stop sign on an interchange leading onto the highway. The participant was instructed to follow the speed limit and signs to the highway straight ahead.

At designated points during the drive, audio prompts instructed participants to take the next exit. Prompts occurred when participants approached the one-mile advanced guide sign and again when nearing the exit ramp. Participants encountered the partially automated truck platoon in the right through lane of the highway during one of three performed maneuvers: continue straight (through), exit the highway, or enter the highway.

After completing all 18 trials, participants sat at a table and completed an electronic questionnaire in which they were asked to describe the meaning of the signs they viewed in the experiment (if any) and explain their experiences and behaviors during the simulated drive. Participants then reported on their perceptions of the simulated platoon and any previous experience driving or working with heavy freight trucks. Once finished, the participants were debriefed and paid.

Participants

Participants comprised 48 licensed drivers from the Washington, DC, metropolitan area, randomly assigned to one of four experimental group conditions. An equal number of males and females were recruited. Twenty-five of the participants were younger than 46 yr. Three participants reported previous experience driving heavy vehicles such as freight trucks. One participant had driven a heavy vehicle once, and the other two had a tenure of 2 and 4 yr, respectively.

ANALYSIS RESULTS

Results are presented in order of the research questions listed in the beginning of the chapter. Data were analyzed using a linear mixed model, mixed-effects beta regression model, mixed-effects logistic regression model, mixed-effects multinomial logistic regression model, or ordered logistic regression model, as specified in the following sections. Drive data from the interchanges where truck platoons were present were the primary interests. Excluded were data from abnormal events, including collision, missed interchange, and speed less than 35 mph when on the main route. In the following analysis, the sign-type group (Control/None, Roadside VMS, On-Truck Sign, and Combined) was the primary independent variable. Gender and age were included as secondary variables. The significance level of 0.05 was adopted.

Entering and Exiting Strategies

Two dependent variables were identified and derived to assess participants' highway entering and exiting strategies under the presence (or absence) of signs related to partially automated truck platoons. The two variables were location relative to truck platoons when entering/exiting and variation in accelerator pedal position.

Location Relative to Truck Platoons when Entering/Exiting (Three Categories: Ahead, Behind, and Between)

Most participants in all sign groups tended to wait before entering the highway until the truck platoon (control/none: 96 percent; roadside: 79 percent; truck-mounted: 92 percent; both roadside and truck-mounted: 100 percent). When no sign or only one type of sign was presented, participants, on a few occasions, cut in between the trucks in the platoons. Maneuvering to get ahead of the truck platoons only occurred in the roadside group and was rare (table 14).

Table 14. Percentage of merge locations for different platoon signs.

Platoon Sign Type	Merge Location When Entering			Merge Location When Exiting		
	Behind	Between	Ahead	Behind	Between	Ahead
Control/none	96	4	0	96	0	4
Roadside	79	12	8	88	0	12
Truck-mounted	92	8	0	83	0	17
Roadside and truck-mounted	100	0	0	96	0	4

When exiting, most participants in all groups stayed behind the truck platoon (control/none: 96 percent; roadside: 88 percent; truck-mounted: 83 percent; both roadside and truck-mounted: 96 percent). Occasionally, participants would pass the truck platoons to exit the highway. No cut-ins occurred when participants were trying to exit.

Statistical analysis conducted using mixed-effect multinomial logistic regression showed insufficient evidence of a relationship between the sign groups and the location relative to the truck platoon when entering or exiting the highway. Also, no statistical evidence of gender or age influence was found.

Variation in Accelerator Pedal Position (Normalized Value between 0 and 1)

The accelerator pedal activity was recorded and transformed into a normalized value between 0 and 1: 0 indicated the participant had not pressed, and 1 indicated the participant had fully pressed the pedal. Average variation in accelerator pedal movement ranged from 0.236 to 0.287 when entering the highway and from 0.163 to 0.220 when exiting the highway. A linear mixed model was conducted, and no significant evidence of a relationship between the sign groups and the variation in accelerator was found for entering or exiting the highway. While age had no significant influence on the accelerator variation either, female participants had 0.0448 ($p = .0272$) more variation than male participants when exiting the highway.

Driving Performance on Through Lanes

Three dependent variables were identified and derived to examine participants' driving performance on the through lanes under the presence (or absence) of signs related to partially automated truck platoons. The three variables were lane choice, steering variability, and immediate following distance with truck platoons.

Lane Choice Percentage (Two Categories: Inner and Outer)

Participants tended to stay on the outer lane during the through trials more than half of the time, regardless of the sign groups (control/none: 62 percent; roadside: 68 percent; truck-mounted: 55 percent; both roadside and truck-mounted: 62 percent). A mixed-effects beta regression showed insufficient evidence of a relationship between the sign groups and the proportion of times that participants spent on the inner lane. Also, no statistical evidence of gender or age influence was found.

Steering Variability (Unit: Degree)

Participants in the roadside sign group had a slightly greater variation in steering compared to the other groups. Variations were generally minimal across the group (control/none: 1.18 degree; roadside: 1.35 degree; truck-mounted: 1.20 degree; both roadside and truck-mounted: 1.20 degree). A linear mixed model was conducted and showed no statistical evidence of a relationship between the sign groups and the steering variability. Similarly, no sufficient evidence of gender or age influence was found.

Immediate Following Distance with Truck Platoons (Unit: Second)

Participants in the truck-mounted sign group tended to stay farther behind the truck platoons compared to the other groups (control/none: 2.76s; roadside: 2.33s; truck-mounted: 3.51s; both roadside and truck-mounted: 2.95s). A linear mixed model showed no statistical evidence of a relationship between the sign groups and the following distance. However, male participants were found to stay 0.662s ($p = .0321$) farther behind the truck than the female participants.

Drivers' Perceptions

After completing the drive, participants were asked their opinions on their feelings about the truck platoons in the post-drive questionnaire. Three dependent variables were identified to evaluate participants' perception under the presence (or absence) of signs related to partially automated truck platoons. The three variables were safe feeling, perceived effort, and opinion about the gap between truck platoons.

Feeling Safe (Scale from 1 = Very Unsafe to 5 = Very Safe)

Participants were asked to rate how safe they felt when entering, exiting, or driving through the highway when a pair of trucks were nearby. Those in the control/none and roadside sign groups tended to report higher safe ratings than the other two groups, regardless of the sections on the simulated highway (table 15).

Table 15. Average rating of safe feeling for different platoon signs.

Platoon Sign Type	Enter	Exit	Through
Control/none	3.2	3.8	3.9
Roadside	3.2	3.5	3.8
Truck-mounted	2.8	3.2	3.2
Roadside and truck-mounted	2.3	2.5	2.8

Statistical analysis using ordered logistic regression showed insufficient evidence of a relationship between the sign groups and the safe rating for the entering section. The same analysis applied to the exiting and through sections showed significant evidence that the participants in the combined sign group would be more likely to give lower safe ratings. The odds of safety being rated higher on the scale when in the combined sign group were 85.3 percent ($p = .0182$) and 82.6 percent ($p = .0271$), less likely than not in the combined sign group for the exiting and the through sections, respectively.

No statistical evidence of gender or age influence was found for the entering and exiting sections. For the through section, the odds of the younger group reporting a higher safety rating was 68.7 percent ($p = .0036$) less likely than the older group.

Perceived Effort (Scale from 1 = Minimal Effort to 5 = Extreme Effort).

The participants were asked to rate the amount of effort they felt was required when entering, exiting, or driving through the highway when a pair of trucks was nearby. Neutral effort ratings were generally reported for entering and exiting sections while the through section was perceived to require less effort to drive (table 16). Statistical analysis using ordered logistic regression showed no statistical evidence of a relationship between the sign groups and the effort rating for all three sections. No sufficient evidence of gender or age effect was found either.

Table 16. Average rating for perceived effort for different platoon signs.

Platoon Sign Type	Enter	Exit	Through
Control/none	3.2	2.8	2.8
Roadside	3.3	3.2	2.6
Truck-mounted	3.3	3.4	2.6
Roadside and truck-mounted	3.5	3.2	2.9

Gap in Truck Platoons (Scale from 1 = Much Shorter than Average to 5 = Much Longer than Average)

Near the end of the questionnaire, the participants were asked to compare the distance between the pairs of trucks throughout the experiment to typical distances they would often see in real life. The average ratings from each group indicated most participants reported shorter than average (control/none: 2.4; roadside: 2.1; truck-mounted: 1.8; both roadside and truck-mounted: 2.2). No statistical evidence of a relationship between the sign groups and the rating was found. Gender and age had no significant effect either.

DISCUSSION

The study evaluated the effects of recommended signing information on truck platooning placed on the roadside and on trucks to examine their influences on light-vehicle drivers' behavior. The experiment as conducted did not find sufficient evidence to show that the signing had a significant influence on highway merging or exiting behavior. Most participants chose to wait or stay behind the truck platoons before merging or exiting the highway, regardless of signage.

Nevertheless, the study authors observed that participants were more likely to go ahead of the truck platoons when exiting than entering the highway, while the cut-in behavior happened more often when participants were entering than exiting the highway. Also, participants generally engaged more with the accelerator when entering than exiting the highway, although no significant evidence about the signing effect was detected. One possible explanation for this conservative merging and exiting strategy might be the speed limit of 55 mph implemented in the simulation. Participants were told to follow the speed limit and the audio instructions as much as possible. An audio warning would be triggered if speeding behavior lasting for at least five seconds was detected. Trucks were also programmed to travel at 55 mph. So, a participant who attempted to pass the truck platoons would likely be speeding and receive a warning. As a result, participants were essentially restricted to driving at a 55-mph range, which may have made them reluctant to pass the truck platoons, even if they would do so in a real-world scenario. In the questionnaire, some participants complained about the speed limit when asked to provide feedback regarding the scenarios. For future experiments using the miniSim simulator, the study authors recommend loosening the speed limit, enhancing ambient vehicle behavior, and other improvements in the simulated environment to better match real-world scenarios.

When driving on the through sections on the highway, participants who saw truck-mounted signs appeared to spend more time on the inner lane, which was considered riskier behavior due to more lane changing; participants needed to change from the inner lane back to the outer lane when instructed to take the exit at the upcoming interchange. Although the effect of signing on the lane choice was not statistically significant, participants in the roadside sign group spent more time on the outer lane than the other groups, on average following at the shortest immediate distance of 2.33 s when truck platoons were ahead.

Questionnaire responses showed that participants who saw truck-mounted signs, especially those who saw both roadside and signs on the truck, felt significantly more unsafe than those in the control/none group when driving on exiting and through sections. Those who saw either roadside signs or no signs reported feeling that driving required less effort than those who saw truck-mounted signs, although the effect of signing on driving effort was not significant. Some participants reported feeling uncomfortable when seeing or driving near trucks. The negative feeling could persist even after seeing the truck-mounted sign intended to provide information to reduce negative feelings.

In summary, based on the results from the driving data and the questionnaire responses, roadside CMS signs appeared to be a better option since they introduced relatively low-risk driving behavior (staying on the outer lane longer) and made driving seem safer and less effortful to participants. The implementation of roadside signs might also be easier, faster, and more economical since these signs can be integrated into the current transportation system that controls CMS signs on the highway.

CHAPTER 6. DRIVING SIMULATOR STUDY 2—EFFECTS OF TRUCK PLATOON CONFIGURATION ON LIGHT-VEHICLE DRIVER BEHAVIOR

As mentioned in the literature review presented in chapter 2, near-term platoon deployments will mostly include two or three trucks. But how light-vehicle drivers' behavior may change in response to two standard-size platooning trucks compared to three is unclear. The sheer size of a group of trucks traveling closely may pose a physical obstacle to light-vehicle drivers. In addition, the gap between the trucks may potentially influence light-vehicle drivers. Research has shown that at longer following distances, light-vehicle drivers may be more likely to cut in between the platooning trucks (Lank, Haberstroh, and Wille 2011; Nodine et al. 2017), which will affect not only the efficiency in platooning operations but also the safety of light-vehicle drivers. A systematic investigation of gap lengths and platoon sizes will help to establish effective practices for platoon operations ahead of widespread deployment. This chapter describes an experiment that investigates the effects of baseline (0.6 s) and longer gaps, and potential lengths of a partially automated platoon on light-vehicle drivers traveling on the highway. The results of the experiment will inform future studies on partially automated platoons to help improve roadway safety and support the successful operation of the platoon.

The objective of this study is to investigate the effects of truck platoon size (two- or three-truck platoon) and gap distance (0.6, 0.9, or 1.2 s) between the trucks on light-vehicle drivers' behavior when entering, exiting, or traveling straight on the highway. The three key research questions examined include the following:

- Do light-vehicle drivers' strategies for entering and exiting the highway vary with the difference of platoon characteristics?
- Does driving performance on the through lanes differ when light-vehicle drivers are driving near partially automated truck platoons of different characteristics?
- Do drivers' perceptions of effort and safety differ when performing certain maneuvers near partially automated truck platoons, and do these perceptions change depending on different platoon characteristics?

Due to a focus on early deployment, this second driving simulator study shared the same assumptions as the first simulator study described in chapter 5.

METHOD

This section describes data collection methods and the experiment administered to participants. The study was conducted using the same miniSim driving simulator and the same simulated highway as described in chapter 5.

Apparatus

The study was conducted using the NADS quarter-cab miniSim in the Human Factors Laboratory at TFHRC. Three 48-inch high-definition screens displayed the forward roadway, side mirrors, and rearview mirrors, with dashboard information presented on an additional

12-inch screen. The simulator had a fixed base with an automotive steering wheel and column, pedals, and gear selector. A subwoofer beneath the driver's seat generated road feel.

Design

Participants were assigned to one of three experimental groups, which determined the gap between trucks in a platoon they would encounter during driving (table 17).

Table 17. Gap conditions by experimental group.

Group	Platoon Gap (s)
1	0.6
2	0.9
3	1.2

During the drive, participants completed a total of 18 trials. On each trial, participants were instructed to either exit and reenter the highway or continue straight. Participants encountered two- or three-truck platoons (figure 19 and figure 20) at six predetermined intervals, including entering, exiting, and through areas (table 18). The order and characteristics of trials remained the same for the three groups of participants.

Source: FHWA.

Figure 19. Illustration. Participants observing the two-truck platoon during driving simulator experiment.

Source: FHWA.

Figure 20. Illustration. Participants observing the three-truck platoon during driving simulator experiment.

Table 18. Description of trials encountered throughout the Study 2 experimental drive.

Trial	Maneuver	Platoon	Platoon Conflict Location
1	Through	—	—
2	Exit/enter	—	—
3	Exit/enter	Three-truck platoon	Enter
4	Through	—	—
5	Exit/enter	—	—
6	Through	Two-truck platoon	Through
7	Exit/enter	—	—
8	Through	—	—
9	Exit/enter	Two-truck platoon	Exit
10	Exit/enter	—	—
11	Through	Three-truck platoon	Through
12	Exit/enter	—	—
13	Through	—	—
14	Exit/enter	Three-truck platoon	Exit
15	Through	—	—
16	Exit/enter	—	—
17	Exit/enter	Two-truck platoon	Enter
18	Through	—	—

— not applicable.

The partially automated platoon consisted of two or three standard U.S. tractor-trailer sleeper cab trucks with approximately 53-ft-long trailers. The total truck length was roughly 70.5 ft from end to end. The trucks had similar but not overtly identical markings. The trucks were simulated using CACC with speed control to maintain a consistent speed of 55 mph, in adherence to the posted speed limit. The following truck maintained a following distance of 0.6 s (48.4 ft), 0.9 s (72.6 ft), or 1.2 s (96.8 ft) behind the lead truck. To account for realistic fluctuations in following distance due to imperfect vehicle sensors and acceleration systems, the following distance randomly varied by ±0.05 s (±4 ft) throughout the drive. The lead truck followed light vehicles at a following distance of 2 s (161.32 ft). If a participant's vehicle merged in between the two trucks, the following truck would adopt a following distance of 2 s.

Buildings in the roadside environment were added as visuals to suggest that vehicles were traveling at 55 mph on the highway. Collisions (in which the participant's simulated vehicle contacts another simulated vehicle or structure) were recorded but not animated, such that the passenger vehicle driver did not hear or see additional indicators of the collision and could continue driving without interruption. Traffic consisting of light-to-medium-weight vehicles and occasional single freight trucks was present in the participant's lane of travel and at interchanges at designated points. With the exception of the approach to through event trials, simulated traffic was restricted to the left travel lane. Two- and three-truck platoons in the opposite direction of travel were presented on occasion. Occasional noninteractive cross-traffic vehicles were presented on the interchange throughout the scenario for realism and to reduce suspicion that an event would occur. Prior to trials with a platoon on the through lanes, large vehicles (e.g., utility van) might enter the highway ahead of the participant to occlude their view of the traffic ahead. The scenario simulated daytime clear weather road conditions.

Procedure

Each session began with participants reviewing and signing the informed consent form. The researchers checked participants' driver's licenses and then assessed participants' vision to ensure a minimum acuity of 20/40 (with correction).

Participants completed a 5–10 min practice drive to experience what they were about to see and perform in the miniSim driving simulator. During the practice drive, participants were also instructed to accelerate to 55 mph and take the exit and merge back onto the highway. Before and after the practice drive, participants were also given an SSQ to screen for symptoms of simulator sickness that may have prohibited participation in the simulation. Once cleared, participants then proceeded with the assigned experimental scenario.

Each participant was instructed to follow the speed limit and signs to the highway straight ahead. At designated points during the drive, audio prompts instructed participants to take the next exit. Prompts occurred when participants approached the one-mile advanced guide sign and again when nearing the exit ramp. Participants encountered the partially automated truck platoon in the right through-lane of the highway while they performed one of three maneuvers: continue straight (through), exit the highway, or enter the highway.

After completing all 18 trials, participants sat at a table and completed an electronic questionnaire on a laptop. Participants were asked about the maximum number of trucks viewed in a platoon, their perceptions of the simulated platoon, their behaviors during the simulated drive, and any previous experience they had driving or working with heavy freight trucks. Once finished, the participants were debriefed and paid.

Participants

Participants comprised 36 licensed drivers from the Washington, DC, metropolitan area, randomly assigned to one of three experimental group conditions. None of the participants took part in the first driving simulator study. Equal numbers of males and females were recruited. Nineteen of the participants were younger than 46 yr. Three participants reported previous experience driving heavy vehicles, such as freight trucks, with two participants having less than 3 yr of experience and one with a tenure of 25 yr.

ANALYSIS RESULTS

This section describes the results of the three research questions listed earlier. Depending on the data characteristics, the following statistical models were used, including linear mixed model, mixed-effects beta regression model, mixed-effects gamma regression model with log link, mixed-effects multinomial logistic regression model, and ordered logistic regression model. The primary interest was in data collected from the interchanges where truck platoons were present. Data from abnormal events, including collisions between participants' vehicles and other objects, missed interchanges, and speed less than 35 mph when on the main route were excluded. In the following analysis, the platoon gap (0.6-, 0.9-, and 1.2-s) and size (two- and three-truck platoons) were the primary independent variables. Gender and age were included as secondary variables. A significance level of 0.05 was adopted.

Entering and Exiting Strategies

Location Relative to Truck Platoons When Entering/Exiting (Three Categories: Ahead, Behind, and Between)

Table 19 shows the overall percentage of merge location relative to the truck platoon as a function of platoon gap and size when participants entered or exited the highway. All participants in the 0.6-s gap group waited until the platoon passed to enter the highway, regardless of the platoon size. Cut-in behavior appeared among participants in the 0.9-s and 1.2-s gap groups, especially when a three-truck platoon was presented. Approximately 73 percent of all cut-ins to a three-truck platoon occurred between the second and the third truck. Maneuvering to get ahead of the truck platoon only occurred in the 1.2-s gap group, in which encountering a three-truck platoon was rare.

Table 19. Percentage of merge location for different conditions.

Platoon Gap (s)	Platoon Size	Merge Location When Entering			Merge Location When Exiting		
		Behind	Between	Ahead	Behind	Between	Ahead
0.6	Two-truck	100	0	0	83	0	17
0.6	Three-truck	100	0	0	92	0	8
0.9	Two-truck	83	17	0	75	0	25
0.9	Three-truck	42	58	0	100	0	0
1.2	Two-truck	67	33	0	100	0	0
1.2	Three-truck	25	67	8	100	0	0

Most participants stayed behind the platoon when exiting the highway, particularly when a three-truck platoon was on the scene. Occasionally, participants in the 0.6-s gap and 0.9-s gap groups would pass the platoon to exit the highway, especially when a two-truck platoon was presented. No participants cut in the platoon when exiting.

Statistical analysis conducted using mixed-effects multinomial logistic regression showed that participants encountering a three-truck platoon were 9.6 ($p = .0012$) times more likely to cut in as compared to staying behind the platoon when entering the highway. No significant evidence showed that the gap between the trucks could affect participants' decision on whether they would get ahead of, cut in, or stay behind the platoon when entering or exiting the highway. No statistical evidence of gender or age influence was found either.

Variation in Accelerator Pedal Position (Normalized Value Between Zero and One)

The accelerator pedal activity was recorded and transformed into a normalized value between 0 and 1, where 0 indicated the participant did not press the pedal, and 1 indicated the participant fully depressed the pedal. Average variation in accelerator pedal movement across platoon gaps and sizes ranged from 0.232 to 0.309 when participants entered the highway and from 0.166 to 0.206 when participants exited the highway. A linear mixed model showed that the accelerator pedal had 0.0361 ($p = .0214$) more variation when participants encountered a three-truck platoon than a two-truck platoon while entering the highway. No significant evidence of a relationship between the platoon gap distance and the variation in accelerator pedal position was found when participants entered or exited the highway. No statistical evidence of gender or age influence was found either.

Driving Performance on Through Lanes

The researchers identified and derived three dependent variables to examine participants' driving performance on through-lanes when partially automated truck platoons were present. The three variables were lane choice, steering variability, and immediate following distance behind a platoon.

Lane Choice Percentage (Two Categories: Inner and Outer).

Participants tended to stay in the outer lane longer than they did in the inner lane, especially when encountering a three-truck platoon with 1.2-s gap distance (table 20). A mixed-effects beta regression showed a significant interaction effect between the gap group and the platoon size. When a three-truck platoon was presented, the time that participants in the 0.9-s and 1.2-s gap groups spent on the inner lane reflected a 66.2-percent ($p = .0092$) and 67.8-percent ($p = .0064$) drop, respectively, as compared to the 0.6-s gap group. For the two-truck platoon, although participants in the 0.9-s gap group showed more use of the inner lane than the 0.6-s gap group, this difference was not significant. When comparing a three-truck to two-truck scenario within the 0.9-s and 1.2-s gap groups, significant reductions—70.9-percent ($p = .0009$) and 66.5-percent ($p = .0030$)—in the duration of inner lane use were observed. Even though a higher use of the inner lane was observed for the 0.6-s group, when a three-truck platoon was present, higher use of the inner lane was not significant. No statistical evidence of gender or age influence was found.

Table 20. Percentage of lane choice during the through trials.

Platoon Gap (s)	Two-Truck		Three-Truck	
	Inner	Outer	Inner	Outer
0.6	47	53	52	48
0.9	53	47	30	70
1.2	47	53	26	74

Steering Variability (Unit: Degree)

Participants had a slightly greater variation in steering when a two-truck platoon was presented, although the variations were generally minimal across the platoon gaps and sizes, ranging from 1.10 to 1.67. A mixed-effects gamma regression model with log link showed a 22.4-percent ($p = .0007$) reduction in variation when participants encountered a three-truck platoon compared to a two-truck platoon. No statistical evidence of a relationship between the gap groups and the steering variability was found. Similarly, no sufficient evidence of gender or age influence was found.

Immediate Following Distance with Truck Platoons (Unit: Second)

Participants tended to stay farther behind a three-truck platoon (0.6-s gap group: 3.66 s; 0.9-s gap group: 3.56 s; 1.2-s gap group: 4.12 s) than a two-truck platoon (0.6-s gap group: 2.78 s; 0.9-s gap group: 2.82 s; 1.2-s gap group: 3.22 s). A mixed-effects gamma regression model with log link showed neither the platoon size nor the gap group had a significant effect on the following distance. No statistical evidence of gender or age influence was found.

Drivers' Perceptions

After completing the drive, participants were asked in a post-drive questionnaire about their opinions regarding the truck platoons. Questions pertained to how safe participants felt, how much effort they expended when driving near the truck platoons, and their thoughts about the gap distance between the truck platoons.

Feeling Safe (Scale from 1 = Very Unsafe to 5 = Very Safe)

Participants were asked to rate how safe they felt when entering, exiting, or driving through the highway when a truck platoon was nearby. Those in the 0.9-s gap group tended to report relatively higher feelings of safety than the other two gap groups. In addition, participants tended to report lower feelings of safety when encountering a platoon during the through areas as compared to while traversing the entrance and exit areas (table 21).

Table 21. Average rating of safe feeling for different conditions.

Platoon Gap (s)	Two-Truck			Three-Truck		
	Enter	Exit	Through	Enter	Exit	Through
0.6	3.68	3.08	2.67	3.58	3.42	2.58
0.9	3.75	3.25	2.67	3.58	3.58	3.08
1.2	3.17	3.17	2.75	3.08	3.25	2.67

Statistical analysis using ordered logistic regression was conducted for all entering, exiting, and through areas. No significant effect on the platoon size and gap group on the safe rating was observed from any of the three regions. No statistical evidence of gender or age influence was found.

Perceived Effort (Scale from 1 = Minimal Effort to 5 = Extreme Effort)

The participants were asked to rate the amount of perceived effort required for entering, exiting, or driving through the highway when a truck platoon was nearby. Those in the 1.2-s gap group seemed to think less effort was required than those in the other two gap groups. The participants also tended to report lower effort ratings when encountering a platoon in the through area. Moreover, the participants generally reported lower effort ratings when a two-truck platoon was presented (table 22.)

Table 22. Average rating for effort feeling for different conditions.

Platoon Gap (s)	2-Truck			3-Truck		
	Enter	Exit	Through	Enter	Exit	Through
0.6	3.67	3.67	2.33	3.92	3.75	2.58
0.9	3.83	3.92	2.50	3.92	4.00	2.83
1.2	3.25	3.33	2.17	3.58	3.25	2.50

Statistical analysis using ordered logistic regression showed no significant effect of the platoon size and gap group on the effort rating for the entering and exiting areas. The same analysis applied to the through area showed significant evidence that the participants would be more likely to give a greater effort rating when a three-truck platoon was presented. The odds of effort being rated as greater when encountering a three-truck platoon were 4.9 times (p = .0176) more likely than when encountering a two-truck platoon. No sufficient evidence of gender or age effect was found.

Gap in Truck Platoons (Scale from 1 = Much Shorter than Average to 5 = Much Longer than Average)

Near the end of the questionnaire, participants were asked to compare the distance between the platooning trucks throughout the experiment to the typical distances they would see in real life. The average ratings from each gap group indicated that most participants reported the following distance they observed in the experiment was shorter than what they would see in real life (0.6-s gap group: 1.8; 0.9-s gap group: 1.8; 1.2-s gap group: 2.4). An ordered logistic regression showed significant interaction effect between the gap group and gender such that male participants in the 0.9-s gap group were 63.3 times (p = .0048) more likely to give a higher rating than female participants in the same gap group. In other words, in the 0.9-s gap group, female participants tended to feel the gap distance was shorter as compared to male participants.

DISCUSSION

The study evaluated the effects of truck platoon size (two- or three-truck platoon) and gap distance (0.6-, 0.9-, or 1.2-s) between the trucks on light-vehicle drivers' behavior. The experiment showed that platoon size had significant influence on participants' highway merging behavior such that a three-truck platoon could make drivers more prone to perform risky cut-ins. This corresponded to the finding that a greater variation in accelerator pedal position was observed when participants entered the highway, especially when encountering a three-truck platoon, as stepping on the gas periodically was needed to cut into the platoon. During the highway merging scenarios, the longer the gap between the trucks in a platoon, the more likely cut-ins would occur. No one cut into or entered ahead of the platoons with 0.6-s gap distance. Although the data did not provide sufficient evidence, this observation was consistent with the previous research (Lank, Haberstroh, and Wille 2011; Nodine et al. 2017). Participants did not cut in when exiting the highway, but a few participants went ahead of a truck platoon with shorter gap distances. A similar observation was found in the first simulation study, suggesting the possible explanation for this conservative outcome might be the imposed speed limit of 55 mph, which may have made participants unwilling to speed through the truck platoons.

When driving on the through regions on the highway, participants tended to spend more time in the inner lane when a two-truck platoon with 0.9-s gap distance or a three-truck platoon with 0.6-s gap distance was present. This tendency was deemed as risky behavior because it might introduce more lane-changing behaviors. This observation also matched with the finding that participants had a slight but significant greater variation in steering when encountering a two-truck platoon in the through regions. A closer immediate following distance with truck platoons was also observed when a two-truck platoon was on the road as compared to a three-truck platoon, although the difference was not significant.

Questionnaire responses showed that participants generally reported slightly above average ratings in feeling safe when entering or exiting the highway and slightly below average ratings when driving in the through areas, regardless of the platoon gap and size. When asked about effort, participants reported that more effort was required when entering or exiting the highway and less effort was required in the through areas. Participants also reported more effort was needed when a three-truck platoon appeared on the through lanes as compared to a two-truck platoon. Overall, participants from all three gap groups reported that the truck following distance was shorter than average. Several participants mentioned that the trucks were driving too close and that the platoons should have a designated lane.

In summary, the results showed that no specific platoon configuration used in the experiment could minimize risk in all areas on the highway at the same time. Although drivers might be tempted to cut in between a three-truck platoon with longer gaps during highway merging, they may engage in other positive behavior such as reducing lane changing or maintaining longer following distance behind the platoon. Participants expressed a reduction of feeling safe in the through areas while reporting such areas required less effort to drive. One reason might be that drivers had to interact with other traffic in the area in addition to the truck platoon at the same time. As a result, while driving on the through lanes might be less complicated than navigating the merging or exiting areas, people might feel unsafe when driving near a platoon along with other traffic.

CHAPTER 7. CONCLUSIONS

The findings from the Perception of Trucks survey (see chapter 3) suggest that, given the overall negative associations with conventional trucks and the potential benefits of automated platooning, a targeted outreach campaign may be effective in improving public perception of trucks. Signing or marking partially automated truck platoons may have meaningful benefits for light-vehicle drivers' safety and comfort while also preserving the intended operations of the platoon. Such indicators may work in conjunction with outreach campaigns to improve public understanding and awareness. From the findings, the researchers proposed a series of novel platoon signings (figure 8), which were further used in the sign study to investigate comprehension and response to novel automated truck signing.

The results of the Sign Lab Study on Effective Indicators of Partially Automated Truck Platooning (see chapter 4) indicate that signs or indicators influenced drivers' perceptions of the trucks' operations and the relationship between them. Based on the overall behavioral responses, perceptual performance, and subjective rankings, signs R2 and T2 (as shown on figure 8) were found to have greater capability to reflect the status of an active platoon in real time and improve participants' comprehension of the grouped and following nature of the truck platoon. Therefore, these signs were selected to be incorporated into the driving simulator study to evaluate driver behavior in highway merge, through, and exit scenarios near a partially automated platoon.

The first driving simulator study (see chapter 5) evaluated the effects of recommended signing information regarding truck platooning placed on the roadside and the trucks to examine their influences on light-vehicle drivers' behavior. The results from the driving data and the questionnaire responses suggest that roadside CMS signs might be more effective in helping reduce risky driving behavior than truck-mounted signs because roadside signs introduced relatively low-risk driving behavior and made driving seem safer and less effortful to participants. Using roadside signs to convey messages requires coordination with traffic management centers, which poses an additional layer of effort; however, implementing roadside signs might be more economical since messaging can be integrated into the current transportation system that controls CMS signs on the highway.

The second driving simulator study (see chapter 6) evaluated the effects of truck platoon size and gap distance on light-vehicle drivers' behavior. The results showed that no specific platoon configuration used in the experiment could minimize risk in all areas on the simulated highway at the same time. The findings suggest benefits from platoons capable of adjusting their size and the gap between the trucks proactively based on ongoing traffic status and highway sections, particularly the through area, as opposed to staying fixed or adjusting passively through the entire trip. Drivers might react differently to a platoon under different traffic conditions. Therefore, a subsequent study to investigate the effects of platoon configurations under different traffic conditions on light-vehicle drivers may be helpful.

The research summarized in this report suggests that signing information on truck platooning using roadside CMS may be beneficial to drivers on public highways. A further investigation of the platoon configurations with different highway traffic conditions, including a mixed-fleet environment in a more realistic scenario (possibly on a test track), may better help establish effective practices for platoon operations. As truck platooning is expected to be commercially deployed in a mixed-fleet environment in the next several years, more human factors research related to light-vehicle drivers' behavior and attitudes in the presence of truck platoons is needed to enhance roadway safety for all drivers.

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