Investigating the Effects of Reserved Lanes for Commercial Truck Platooning on Congestion: A Pennsylvania Turnpike Case Study

Corey D. Harper, Ph.D., Corresponding Author

Transportation Systems Engineer

Booz Allen Hamilton

20 M St SE

Washington, DC 20003 USA

Tel : +1 410-698-3060 ; Email: cdharper@alumni.cmu.edu

Chris T. Hendrickson, Ph.D.

Hamerschlag University Professor of Engineering Emeritus

Civil and Environmental Engineering

Carnegie Mellon University

5000 Forbes Avenue

Pittsburgh, PA 15213 USA

Tel: +1 412-268-1066 ; Fax: +1 412-268-7813 ; Email: cth@cmu.edu

Constantine Samaras, Ph.D.

Assistant Professor

Civil and Environmental Engineering

Carnegie Mellon University

5000 Forbes Avenue

Pittsburgh, PA 15213 USA

Phone: +1 412-268-1658; Fax: +1 412-268-7813; Email: csamaras@.cmu.edu

Abstract

Connected and automated vehicles (CAVs) have the potential to provide a safer and more efficient transportation system. This paper outlines a method to determine feasible platoon demonstration sites, investigates the impacts of a dedicated truck platoon lane on peak hour traffic flow on the Pennsylvania Turnpike, and discusses possible demonstration designs and highlight those times and days of week where a dedicated platoon lane could have the greatest impacts on congestion. The Pennsylvania Turnpike contains 12 sections where there are at 3 lanes in at least one direction for greater than 2 miles, that could be used as platoon demonstration sites. The results suggest that the five and six lane segments in Western and Central Pennsylvania could be viable options because these areas have relatively low peak hour traffic and a relatively high proportion of vehicles traveling on these road segments are commercial trucks. As a result, high level of service is maintained even at low platoon penetration rates. The 5 and 6 lane road segments located in Eastern Pennsylvania, near Philadelphia, contain road segments that have relatively high peak hour traffic flows and the majority of vehicles traveling on this sections of road are passenger cars. Therefore, dedicating a lane to truck platooning on these sections would have severe impacts on congestion during peak hour travel times. The authors use the Pennsylvania Turnpike as a case study for this analysis but the results and recommendations found within this paper could be applied to other existing roadways as well.

Keywords: Platooning, Freight Transportation, Level of Service, Congestion, Connected Vehicles; Automated Vehicles;

Introduction

Traffic safety and congestion remain significant issues on today's public roadways. The National Highway Traffic Safety Administration (NHTSA) reports that in 2015 there were a total of 6.3 million police reported motor vehicle crashes including, 35,000 fatal crashes and 2.4 million injury crashes, the majority of which occurred due to human error (NHTSA 2017; Singh 2015). In addition to safety concerns, traffic congestion continues to be a problem for everyday commuters who are likely to encounter high levels of congestion in urban and suburban areas when traveling to and from work (Ohnsman 2017), which could create many problems such as, increased fuel consumption, air pollution, and dampened economic growth in heavily congested areas (Barth and Boriboonsomsin 2008; Hymel 2009; Fuglestvedt et al. 2015). Connected and automated vehicles (CAVs) have the potential to provide a safer, more cost-effective, and efficient transportation system, if the proper deployment strategies are implemented (Anderson et al. 2014; Harper et al. 2016). This paper focuses on truck platooning, which could experience widespread adoption in the next 5 to 10 years (Christ 2017). Trucks are ideal applications for platooning since these vehicles drive for long distances along the same route, often concentrated in few corridors, and could greatly benefit from platooning due to their low fuel efficiency.

Platoons are groups of vehicles that follow closely behind one another at high speeds and communicate through connectivity and are an example of Level 1 and Level 2 vehicle automation as defined by the Society of Automotive Engineers (SAE) (SAE, 2016). The first truck in the platoon serves as the lead vehicle with each successive vehicle in the platoon following the lead vehicle with limited driver intervention. Platoons have the opportunity to reduce energy consumption resulting from aerodynamic drag. For example, heavy duty vehicles (HDV) traveling in a platoon can reduce fuel consumption anywhere between 4.5%-8%, depending on the time gap and travel speed of the vehicles in the platoon (Alam et al. 2010). This decrease in fuel consumption could reduce emissions from truck travel and save truck companies considerable amounts of money, as fuel costs are about 1/3 of the total per mile cost to operate a HDV (Torrey and Murray 2015). HDVs, while only comprising about 4% of the total number of registered highway vehicle in the US (Bureau of Transportation Statistics 2016), account for about 23% of the total energy consumed by the transportation sector, in large part due to the low fuel efficiency of these trucks and the large amount of miles a truck travels annually to deliver goods (Energy Information Administration 2016). In the U.S. truck transport is growing at a rapid pace and this trend is likely to continue into the future (Energy Information Administration 2014).

This paper characterizes near and long-term scenarios for the Pennsylvania Turnpike to begin accommodating CAV technologies. An objective of this paper is to aid the Pennsylvania Turnpike in making a more informed decisions on choosing potential platoon demonstration sites and to provide recommendations on those sections that could be feasible options. The authors use hourly traffic flow data from the Pennsylvania Turnpike and estimate changes in peak hour level of service (LOS) if a dedicated truck platoon lane were implemented on selected segments of this road. In addition, the authors discuss possible platoon demonstration designs and highlight those times and days of week where a dedicated platoon lane could have the greatest impacts on congestion. The authors use the Pennsylvania Turnpike as a case study for this analysis due to the robustness of their hourly traffic flow data, but the results and recommendations found within this paper could be applied to other existing roadways as well. A demonstration could be of interest to the Pennsylvania Turnpike and other roadways for proof of concept and the assessment of safety and operational issues. The results in this paper are meant to provide discussion on the potential impacts of platooning on traffic congestion and can help inform near- and long-term roadway design and transportation planning decisions during the transition to CAV transportation.

Literature Review

Several researchers have proposed steps towards transitioning to CAV transportation. For example, Shladover (2000) suggests deployment steps by first defining a set of principles to govern platoon based highway system deployment strategies and proposing a deployment sequence- beginning with adaptive cruise control, transitioning to implementing protected lanes, and ending with the addition of a link and network layer (Shladover 2000). Bayouth and Koopman (1998) propose a set of functional evolution reference models for highways to accommodate CAV transportation: vehicle automation, the addition of inter-vehicle communications, and the addition of infrastructure support. The three-staged reference evolution model presented by Bayouth and Koopman (1998) starts with first automating in-vehicle functions and then adding vehicle communications and infrastructure support as later additions. Tsao (1995) identifies barriers for the deployment of a platoon based highway system and proposes steps for transitioning toward CAV transportation, beginning with an automated shuttle in mixed traffic supervised by a professional driver, followed by the construction of a high-occupancy vehicle (HOV) highway-to-highway connecter ramps and equipping HOV lanes for automated driving. Chen et al. (2017) developed a formulation to examine feasible lane policies to accommodate AVs such as exclusive AV lanes or mixed-traffic lanes and found that the effectiveness of lane policies are highly dependent on the AV penetration rate.

Traffic flows along with long-held assumptions about maximum roadway capacity and volume-delay functions could change with automation. Equipping vehicles with automated technologies will likely reduce crashes and in turn decrease non-recurrent congestion. According to the Federal Highway Administration (FHWA) close to 60% off all road congestion is caused by crashes, construction, or emergencies, which suggests that a more coordinated vehicle fleet could substantially reduce travel times and delay (FHWA 2014). By reducing the average safe inter-vehicle distance between vehicles, highway capacity could increase by as much as 273% when using both sensors and vehicle-to-vehicle communication technologies (Tientrakool et al. 2011). Milanés et al. (2014) presents the design, development, implementation, and testing of a cooperative adaptive cruise control (CACC) systems, which were implemented into four production Infiniti M56s. Milanés et al. (2014) concluded that by introducing vehicle to vehicle (V2V) to cars with adaptive cruise control (ACC) systems enables significant reductions in intervehicular gaps. VanderWerf et al. (2002) concluded that increases in highway capacity increase quadratically with CACC market penetration. Lioris et al. (2017) estimates that platooning can increase saturation flow rates by a factor as large as two or three. The authors focused on a road network near Los Angeles and utilized a discrete event simulation to estimate their results. Researchers at Carnegie Mellon University evaluated the impacts of automated vehicles on 24-hour road volumes on the Parkway East (I-376). They find that automation could increase 24-hour road volumes along this road up to 10% and that reducing lateral lane sizes could increase roadway capacity by allowing for additional lanes to be constructed (Hendrickson et al. 2014). Using simulation, Talebpour et al. (2017) examined the impacts of reserving a lane for AVs on congestion and travel time. It was found that increase throughput at AV penetration rates above 50% and 30% on two and four lane highways, respectively.

This paper makes a contribution to the literature by using the Pennsylvania Turnpike's hourly traffic flow data, which provides information on traffic volumes by vehicle class, to identify potential platoon demonstration sites and to estimate how implementing a truck platoon lane on these portions of the roadway could impact current LOS. This paper has a different objective than previous platooning studies. In particular, this study should enable stakeholders and other organizations to understand the impacts and feasibility of dedicating a lane on existing road networks to truck platooning and presents a method to determine initial testing areas.

Methods & Data

To assess the changes in LOS from reserving a lane for truck platooning, the authors first identify those portions of the Pennsylvania Turnpike that could be suitable to launch a platoon demonstration. Once these sections are identified the authors can then estimate peak hour LOS and how this could change with a reserved lane for truck platooning. The primary source of data for this project are hourly Traffic Flow Reports of the Pennsylvania Turnpike from Monday, May 1, 2017 to Friday, May 5, 2017. The dataset, which was obtained through a "Right to Know" request, contains traffic flow data on both electronic toll collection (ETC) and non-ETC traffic for all 24 hours of the day arranged by vehicle classification type, direction (i.e., East/North or West/South), and turnpike interchange. It should be noted that the reservation of a lane would only be for demonstration purposes and would be open to general traffic once testing is complete. Table 1 (shown below) provides an overview of the methodology in this paper for selecting a feasible platoon demonstration site on the Pennsylvania Turnpike.

Table 1. Methodology for Selecting Feasible Truck Platoon Demonstration Sites on Pennsylvania Turnpike

Step	Description	Notes
1	Identify those portions of the Turnpike with at least 3 lanes in one direction for greater than 2 miles, which the authors categorize to as "potential platoon demonstration sites."	Outlined in “Identification of Potential Platoon Sites on Pennsylvania Turnpike” section of paper
2	Identify those vehicle class definitions that include commercial trucks.	Outlined in “Estimation of Level of Service” section of paper
3	Capture peak hourly traffic flow volumes by vehicle class for potential platoon demonstration sites.	Outlined in “Estimation of Level of Service” section of paper
4	Estimate peak hour level of service (LOS) for each platoon demonstration site using the Highway Capacity Manual.	Refer to Eq. (1) in “Estimation of Level of Service” section of paper
5	Estimate peak hour LOS for each platoon demonstration site if there was a dedicated commercial truck platoon lane, using the Highway Capacity Manual.[a]	Refer to Eq. (2) in “Estimation of Level of Service” section of paper
6	Identify those potential platoon demonstration sites that are able to maintain LOS A or LOS B during peak hour travel, which the authors categorize to as "feasible platoon demonstration sites."	Outlined in the “Results” and “Discussion” sections of the paper

Note: LOS=level of service

[a]Level of service was only estimated for non-dedicated lanes where non-commercial trucks and trucks without platooning capabilities are assumed to travel.

Identification of Potential Platoon Demonstration Sites on Pennsylvania Turnpike

The Pennsylvania Turnpike has a number of roadway sections that could potentially be converted into platoon demonstration sites. The authors develop a sample set of potential platoon demonstration sites by identifying those portions on the Pennsylvania Turnpike with at least 3 lanes in one direction for greater than 2 miles, as shown in Fig. 1. The authors chose this as the filtering criteria because it would not be feasible to dedicate a lane to platooning if there are only 2 travel lanes available and think that a section of at least 2 miles would be required for calibration and robust results. Each entrance and exit interchange combination along the roadway has a separate hourly traffic flow rate. Because the authors are interested in vehicular volumes, if an identified 5 or 6 lane portion of the roadway was continuous and intersects more than one interchange combination, this larger section was divided up into smaller sections representative of the changes in traffic flow rates. For example, Sections 11 and 12, both located in eastern Pennsylvania, are collectively, a continuous 6 lane segment of the Pennsylvania Turnpike that spans about 10 miles, but were divided into 2 different segments to capture the changes in traffic flow rates along this section of the roadway.

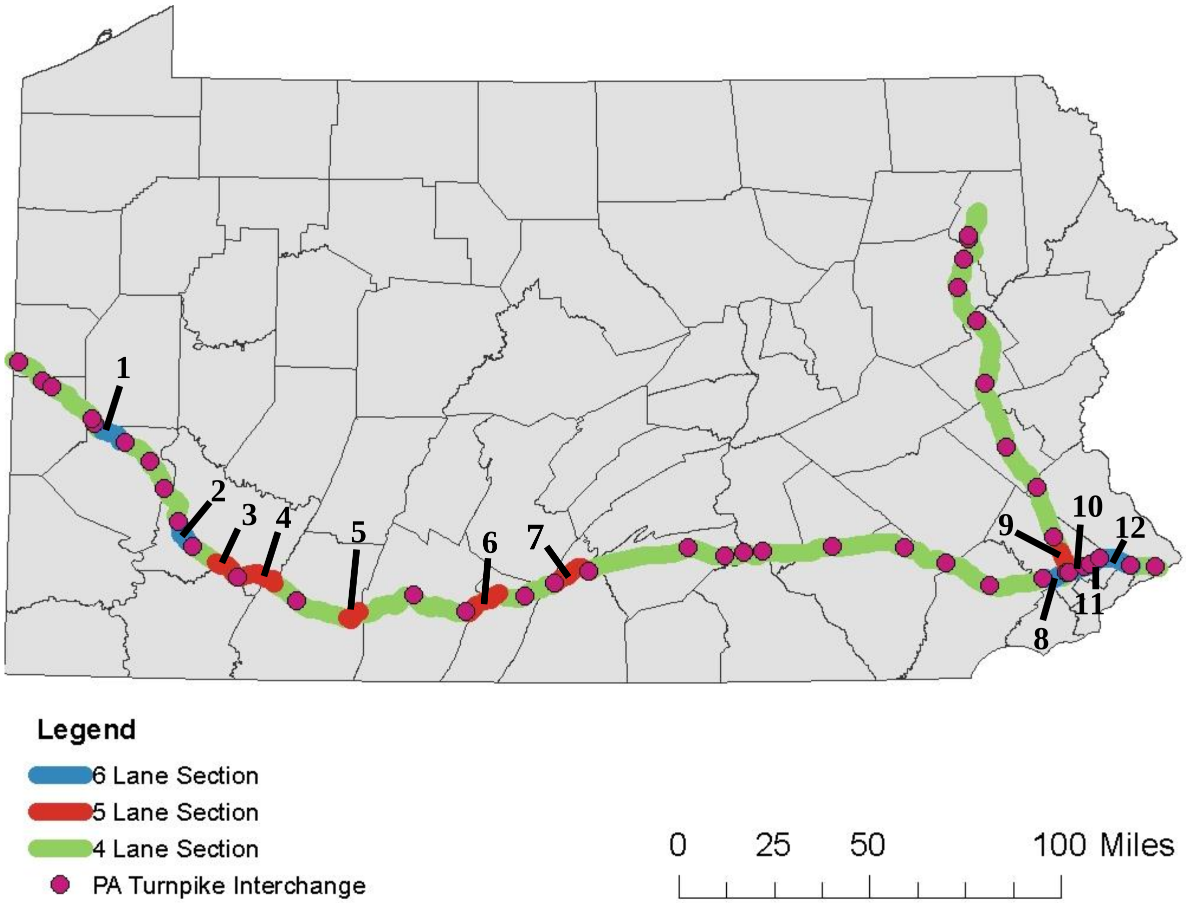


Fig. 1. Five and Six Lane Sections of the Pennsylvania Turnpike Greater than 2 Miles in Distance

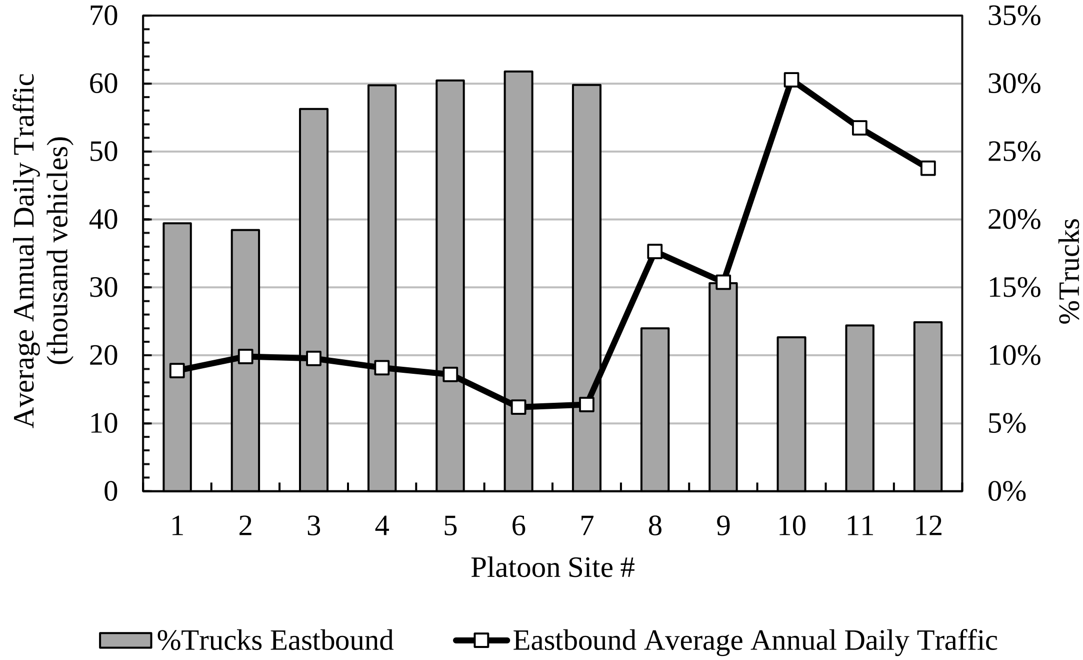
Note: PA Turnpike Interchange= Pennsylvania Turnpike Interchange

The ideal platooning site would be one that maximizes the potential fuel saving benefits of platooning, while minimizing the impacts to the current level of service provided to passenger car and light and medium-truck traffic. Out of the 12 potential platoon demonstration sites identified, half of them have 6 total lanes, 3 lanes in both the east and west directions, while the other half have a total of 5 lanes, with only 3 lines in one direction. Seven sites are located in Western and Central Pennsylvania, respectively, while the remaining 5 sites are located in Eastern Pennsylvania near Philadelphia. Platoon site 7, located in in northern Franklin County, is the longest potential platoon site on the Pennsylvania Turnpike, followed by Platoon Site 4, located in Westmoreland County. In comparison, the overall average annual daily traffic (AADT), is about 5% higher at Platoon Site 7 than Platoon Site 4, with truck traffic being about the same at both sites. Platoon Site 12 has the highest AADT in both directions. Platoon sites 11, 12, and 13, all located in Montgomery County, have both the highest AADT and the lowest proportion of truck traffic, when compared to the other platoon sites. There are about 108,000 total vehicles that travel on platoon site 12 throughout the course of the day, while there are about 92,000 vehicles that travel on platoon site 13 each day. Platoon site 11 has the highest AADT when compared to the other sites, there are about 120,000 total traveling on this platoon site each day but only about 14,000 or 11% of these vehicles are trucks. Platoon site 7, has the highest proportion of truck traffic, with trucks making up about 30 and 33 percent of vehicles traveling in the east and westbound directions, respectively. In addition, platoon sites 3, 4, 5, and 6 all have a relatively high proportion of trucks traveling on these sections on the Pennsylvania Turnpike. Overall, eastbound traffic flow rates are slightly higher than those in the westbound direction, but there are a slightly higher proportion of trucks traveling westbound. The location and length of each potential platoon site is outlined in Table 2. The AADT values (shown below in Fig. 2.) provide a simple and useful measurement of how busy each platoon site is over the course of a typical day. In the next section the authors will discuss how hourly traffic volume was converted to passenger car equivalent units to assess the peak hour traffic flow and LOS at each platoon site.

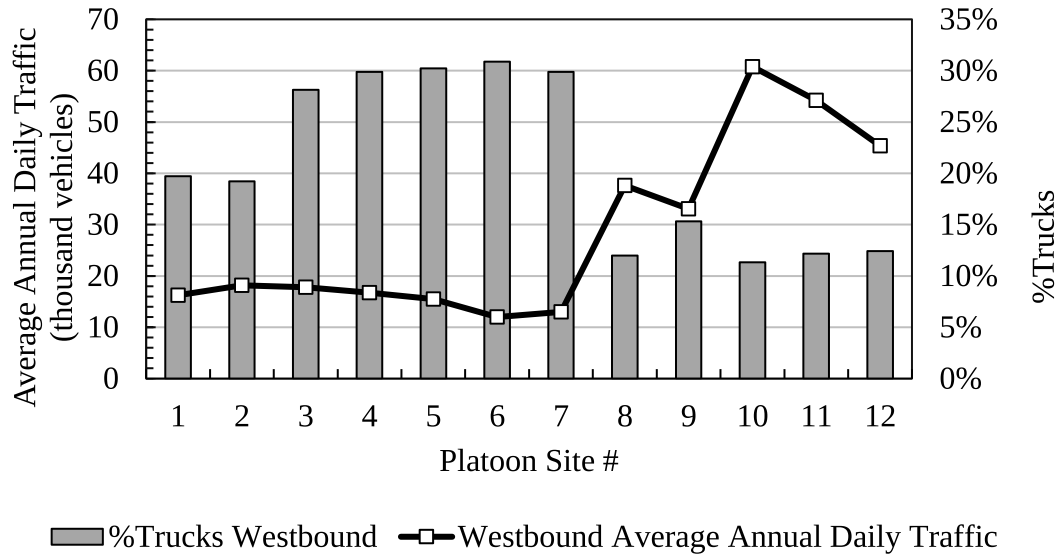
Table 2. **Five and Six Lane Sections of Pennsylvania Turnpike Location and Length by Platoon Site**

Platoon Site #	No. Lanes	3 Lane Direction	Interchange	Interchange	County	Length (miles)
1	6	Both	Warrendale	Butler Valley	Allegheny	6.2
2	6	Both	Irwin	New Stanton	Westmoreland	7.3
3	5	East/North	New Stanton	Donegal	Westmoreland	7.9
4	5	East/North	Donegal	Somerset	Westmoreland	9.4
5	5	West/South	Somerset	Bedford	Somerset	5
6	5	East/North	Breezewood	Fort Littleton	Fulton	3.4
7	5	West/South	Willow Hill	Blue Mountain	Franklin	10.5
8	6	Both	Valley Forge	Norristown	Montgomery	5.9
9	5	West/South	Mid-County	Lansdale	Montgomery	6
10	6	Both	Mid-County	Fort Washington	Montgomery	4.1
11	6	Both	Fort Washington	Willow Grove	Montgomery	2.6
12	6	Both	Willow Grove	Bensalem	Montgomery	7.8

Note: Each 5 and 6 lane road segment is designated a number starting from the left of the Figure 1 and increases as you move east along the Pennsylvania Turnpike.



(a)



(b)

Source: Pennsylvania Turnpike Monthly Traffic Flow Reports from January, 2016 to December, 2016.

Note: % Trucks includes Light (>7,000 lbs.), Medium, and Heavy duty trucks; no passenger cars are included in this estimate.

Fig. 2. (a) Pennsylvania Turnpike Average Annual Daily Traffic and Proportion of Trucks in Eastbound Direction by Platoon Site. **(b)** Pennsylvania Turnpike Average Annual Daily Traffic and Proportion of Trucks in Westbound Direction by Platoon Site

Estimation of Level of Service

As mentioned previously, the Pennsylvania Turnpike reports its traffic flow data by vehicle classification group. The Pennsylvania Turnpike does not follow the Federal Highway Administration's (FHWA) 13 category vehicle group classification (Hallenback et al. 2014). Instead, the Pennsylvania Turnpike follows a 9-category vehicle group classification system (Pennsylvania Turnpike Commission 2017), for the purposes of calculating toll rates, as shown below in Table 3. The Pennsylvania Turnpike arranges all passenger cars into one group, with the other 8 classes grouped in terms of vehicle weight. In the state of Pennsylvania, a commercial motor vehicle is defined as a single-vehicle with a gross vehicle weight of 26,001 or more pounds (Pennsylvania Department of Transportation 2015). Since the authors are interested in estimating the congestion impacts of devoting a lane for commercial truck or heavy duty vehicle platooning, the authors focus on those trucks in vehicle class groups 5 to 9 for the remainder of this analysis. Although class group 4 does contain some commercial trucks by definition, non-commercial trucks are also grouped into this category. Since there is no way to distinguish non-commercial and commercial trucks in class group 4 from the data given, the authors treat all vehicles in this group as non-commercial vehicles for the purpose of this analysis.

Table 3. Pennsylvania Turnpike Vehicle Class Definitions

Class Group	**Class Definition**
1	Passenger Car
2	7,001 to 15,000 lbs.
3	15,001 to 19,000 lbs.
4	19,001 to 30,000 lbs.
5	30,001 to 45,000 lbs.
6	45,001 to 62,000 lbs.
7	62,001 to 80,000 lbs.
8	80,001 to 100,000 lbs.
9	100,001 lbs. and over

Source: Pennsylvania Turnpike Commission. *Toll Schedule 2017*. Harrisburg, PA, 2017.

The Pennsylvania Turnpike's hourly traffic flow data contains information on the number of vehicles that pass between two successive interchanges in each direction during each hour of the day. The presence of heavy vehicles in the traffic stream decreases the free flow speed (FFS) as these vehicles take up more roadway space and behave differently than a passenger car would under certain conditions (weather, steep road grades, etc.). In order to assess the overall effect of each vehicle type on traffic operations, the hourly traffic volumes were converted to an equivalent flow rate expressed in terms of passenger cars equivalence (pce). For simplicity, the authors assumed that each platoon site has a rolling terrain and that there is no single grade at any platoon site that has a significant impact on traffic operations. The pce conversion factor for trucks and buses on extended general highway segments on rolling terrains, as defined by the Highway Capacity Manual (HCM) (Transportation Research board 2010), was applied to all vehicles outside of class group 1 and summed together to estimate the passenger car pce volume during peak hour traffic. The 2010 HCM provides pce values for trucks and recreational vehicles (RVs) as a function of terrain (grade and length of grade), but does not provide pce equivalent estimates as a function of vehicle weight. Some of the vehicles included in classes 2-4 may be RVs or U-Hauls, hence as a result the pce estimate provided here is more conservative. The authors choose to focus on peak hour traffic for this analysis since this is the time of day that a dedicated truck platoon lane could have the most significant impact on traffic operations. The eastbound peak hour traffic volume, expressed in passenger cars per hour (pce/hr) is the sum of the number of passenger cars and the pce number of trucks and is expressed in Eq. (1):

$$Vol_{East_i} = [PC_{East_i} + (R \times Trucks_{East_i})] \tag{1}$$

where Vol_{East_i} is the total eastbound peak hour traffic volume (pce/hr) at platoon site i, PC_{East_i} is the eastbound peak hour passenger car traffic volume at platoon site i, R is the passenger car equivalent conversion factor trucks and buses for extended general highway segments on rolling terrains ($R = 2.5$), $Trucks_{East_i}$ is the number of light (>7,000 lbs.), medium, and heavy duty trucks traveling on platoon site i during peak hour traffic in the eastbound direction. The traffic flow rate (pc/hr/ln) can be estimate by dividing the passenger car equivalent traffic volume by the number of lanes, which in each case is 3. Once the traffic flow rate, the authorsrefer to the 2010 HCM Basic Freeway Segments Speed-Flow Curve and using a free flow speed of 70 mi/h estimate peak hour LOS. A similar method can be followed to estimate peak hour passenger car equivalent traffic flow rate in the westbound direction.

Each potential platoon site has at least 3 lanes in one direction and travel in any of these lanes is not restricted by time of day, vehicle class group or occupancy. In order to estimate changes in peak hour LOS, the authors repurpose one lane at each platoon site where originally any car could travel and restrict travel in this lane to commercial trucks with platoon capabilities, which the authors will refer to as the dedicated truck platoon lane. All passenger cars, vehicles in class groups 1 through 4, and commercial trucks without platooning capabilities, are now only permitted to travel in the "non-dedicated lanes" and are restricted to two lanes of travel instead of three. In this model, platoon penetration rates determine the number of connected and automated commercial trucks that will make use of the dedicated platoon lane, which the authors assume to be uniform across each platoon site on the Pennsylvania Turnpike. For example, a platoon penetration rate of 25% means that 25% of all commercial trucks at each platoon site are now assumed to have platooning capabilities and will choose to use the dedicated platoon lane. The estimated peak hour LOS when there is a dedicated truck platoon lane, refers to the quality of traffic service in the non-dedicated platoon lanes; the traffic operations in the dedicated truck platoon lane are assumed to be free flow at high traffic density. Peak hour traffic volumes for each vehicle class are assumed to remain constant for the purpose of this analysis, when there is a dedicated lane. The eastbound peak hour traffic flow rate when there is a dedicated platoon lane is estimated using the following method, expressed in Eq. (2):

$$Vol_{Platoon-East_i} = Vol_{East_i} \times [1 - (C_{East_i} \times AV)] \tag{2}$$

where $Vol_{Platoon-East_i}$ is the eastbound peak hour traffic volume (pce/hr) when there is a dedicated platoon lane at platoon site i, Vol_{East_i} is the total eastbound peak hour traffic volume (pce/hr) at platoon site i and is expressed on Eq. (1), C is the proportion of commercial trucks traveling during peak hour on platoon site i, AV is the commercial truck platoon penetration rate, which is assumed to be uniform at all platoon sites. The traffic flow rate (pce/hr/ln) when there is a dedicated platoon lane can be estimated by diving the peak hour traffic volume by the number of non-dedicate lanes, which in each case is 2. Once the traffic flow rates are estimated, the authors refer to the 2010 HCM Basic Freeway Segments Speed-Flow Curve and using a free flow speed of 112 km/h (70 mi/h) estimate peak hour LOS. A similar method can be followed to estimate peak hour passenger car equivalent traffic flow rate, when there is a dedicated platoon lane in the westbound direction.

Results

An objective of this paper is to estimate how implementing a platoon lane on existing highways could impact traffic conditions. We start by estimating the impacts from a point in time where platooning technologies have only been partially adopted and are only implemented on brand new trucks to a point in time where the truck industry transitions to total market penetration. From these results, we discuss how the Pennsylvania Turnpike and other existing roadways could begin to transition towards CAV transportation.

Peak Hour Level of Service on Pennsylvania Turnpike

There are several potential platoon sites on the Turnpike where there is free flow (LOS A) and reasonable free-flow (LOS B) traffic during peak hour travel times. At each potential platoon site, passenger cars make up the majority of vehicles traveling during peak hour traffic in both directions. In the eastbound direction peak hour tends to occur during the early evenings, between 4PM and 5PM, most commonly on Thursdays and Fridays. In comparison, peak hour travel in the westbound direction tends to occur in the mornings, between 6AM and 8AM, most commonly on Tuesdays and Fridays. In the eastbound direction, platoon sites 2, 3, 4, and 6 operate at LOS A during peak hour traffic, which means that vehicles are unimpeded in their ability to maneuver within the traffic stream. Platoon site 1 operates at LOS B in the eastbound direction, which indicates that vehicles traveling during peak hour are almost completely unimpeded in their ability to move within the traffic stream. In the westbound direction, platoon sites 1, 2, 5, 7, and 8 all operate at LOS A during peak hour traffic, while the remaining sites operate at LOS D or below, which indicates that maneuverability is low and traffic operations are approaching capacity. In both directions, platoon sites 9, 10, 11, 12, and 13 have the highest peak hour traffic volumes and the lowest LOS grades when compared to the other platoon sites, and have relatively low amounts of commercial truck traffic. For example, there are about 6,400 passenger car equivalent vehicles traveling from the Fort Washington to Mid-County interchange (Platoon site 10) during peak hour travel with 90 and 6 percent of these vehicles being passenger cars and commercial trucks, respectively. Platoon sites 7 has a relatively low peak hour traffic volumes, but a very high proportion of vehicles traveling through this section are commercial trucks. Table 4 and Table 5 show the east and westbound peak hour traffic volumes in terms of passenger car equivalent units, as well as the peak hour flow rate, expressed in terms of passenger cars per hour per lane (pce/ln/hr), and LOS for each potential platoon site.

Table 4. Peak Hour Level of Service on Pennsylvania Turnpike by Platoon Site in the Eastbound Direction

Platoon Site #	Day of Week	Eastbound Peak Hour	Eastbound Peak Hour Traffic Volume (pce/hr)	% Commercial Trucks[a]	Peak Hour Traffic Flow Rate (pce/ln/hr)	LOS
1	Thursday	4PM-5PM	2,500	16%	840	B
2	Friday	4PM-5PM	2,300	12%	760	A
3	Friday	11AM-12PM	2,200	26%	730	A
4	Friday	12 PM- 1PM	2,000	27%	680	A
5	na	na	na	na	na	na
6	Friday	11AM-12PM	2,000	26%	650	A
7	na	na	na	na	na	na
8	Friday	1PM-2PM	4,700	4%	1,600	C
9	Thursday	4PM-5PM	4,200	10%	1,400	C
10	Friday	3PM-4PM	6,400	6%	2,100	E
11	Friday	4PM-5PM	6,000	6%	2,000	D
12	Thursday	4PM-5PM	5,700	6%	1,900	D

Note: pce= Passenger Car Equivalence ; NA= Not Applicable

[a]Weighted percentage based on passenger car equivalence.

Note: Values only reported for those potential platoon sites that have 3 lanes in eastbound direction.

Note: The number of total travel lanes for each potential platoon site is 3.

Note: Posted speed limit is 112 km/hr (70 mi/hr) at each platoon site.

Table 5. Peak Hour Level of Service on Pennsylvania Turnpike by Platoon Site in the Westbound Direction

Platoon Site #	Day of Week	Westbound Peak Hour	Westbound Peak Hour Traffic Volume (pce/hr)	% Commercial Trucks[a]	Flow Rate (pce/ln/hr)	LOS
1	Tuesday	7AM-8AM	2,100	22%	710	A
2	Friday	7AM-8AM	2,000	16%	670	A
3	na	na	na	na	na	na
4	na	na	na	na	na	na
5	Friday	1PM-2PM	2,100	27%	700	A
6	na	na	na	na	na	na
7	Friday	2PM-3PM	1,100	48%	370	A
8	Tuesday	7AM-8AM	5,300	8%	1,800	D
9	Tuesday	6AM-7AM	4,100	11%	1,400	D
10	Friday	6AM-7AM	7,100	7%	2,400	E
11	Friday	6AM-7AM	6,000	11%	2,000	D
12	Thursday	6AM-7AM	5,600	12%	1,900	D

Note: pce= Passenger Car Equivalence ; na= Not Applicable

[a]Weighted percentage based on passenger car equivalence.

Note: Values only reported for those potential platoon sites that have 3 lanes in eastbound direction.

Note: The number of total travel lanes for each potential platoon site is 3.

Note: Posted speed limit is 112 km/hr (70 mi/hr) at each platoon site.

Level of Service on Turnpike with Dedicated Truck Platoon Lane

The Pennsylvania Turnpike has several sections where implementing a commercial truck platoon demonstration site could be a viable option. At very low penetration rates, the LOS decreases the at most platoon sites, with the exception of platoon site 7 going westbound, which never experiences a decrease in LOS at any penetration rate, even if there were no trucks platooning during peak hour traffic. This is most likely due to the relatively low peak hour traffic volume and high proportion of commercial trucks traveling on this roadway section during peak hour travel. Sections 1, 2, 3, and 4 could also be viable options for implementing a platoon lane even at low penetration rates and in both directions. While, LOS does decrease during peak hour traffic, the current LOS in these sections are already high so motorists still have a high level of physical and psychological comfort and are able to travel at the posted speed even with a dedicated platooning lane. The LOS on these sections never reach free flow, even when all commercial trucks are diverted to the dedicated platoon lane, because of the high volume of passenger cars and non-commercial trucks traveling on this road during peak hour traffic. The only way to achieve LOS A would be to construct another non-dedicated lane for travel. On the other hand, Platoon sites 8 through 13, currently have low LOS and proportionally low truck traffic during peak hour travel in both directions, so reserving a lane for platooning only decreases the LOS to the point where all passenger cars and trucks without platooning capabilities traveling on these portions of the Pennsylvania Turnpike move in lockstep with the vehicle in front of it, with frequent slowing required. Table 6 and Table 7 display how LOS on the Pennsylvania Turnpike changes with a dedicated platoon lane.

Table 6. Eastbound Level of Service with Dedicated Platoon Lane by Platoon Penetration Rate

Platoon Site #	% Commercial Trucks[a]	Current Peak Hour Traffic Flow Rate (pce/ln/hr)	Peak Hour LOS	Commercial Truck Platoon Penetration Rate 0%	5%	25%	50%	75%	100%
1	16%	840	B	C	C	B	B	B	B
2	12%	760	A	B	B	B	B	B	B
3	26%	730	A	B	B	B	B	B	B
4	27%	680	A	B	B	B	B	B	A
5	na	na	na	na	na	na	na	na	na
6	26%	650	A	B	B	B	B	B	A
7	na	na	na	na	na	na	na	na	na
8	4%	1,600	C	E	E	E	E	E	E
9	10%	1,400	C	D	D	D	D	D	D
10	6%	2,100	E	F	F	F	F	F	F
11	6%	2,000	D	F	F	F	F	F	F
12	6%	1,900	D	F	F	F	F	F	F

[a]Weighted percentage based on passenger car equivalence.

Note: pce= Passenger Car Equivalence ; na= Not Applicable

Note: Values only reported for those potential platoon sites that have 3 lanes in eastbound direction.

Note: Posted speed limit is 112 km/hr (70 mi/hr) at each platoon site.

Table 7. Westbound Level of Service with Dedicated Platoon Lane by Platoon Penetration Rate

Platoon Site #	% Commercial Trucks[a]	Current Peak Hour Traffic Flow Rate (pce/ln/hr)	Current Peak Hour LOS	Commercial Truck Platoon Penetration Rate 0%	5%	25%	50%	75%	100%
1	22%	707	A	B	B	B	B	B	B
2	16%	672	A	B	B	B	B	B	B
3	na	na	na	na	na	na	na	na	na
4	na	na	na	na	na	na	na	na	na
5	27%	696	A	B	B	B	B	B	A
6	na	na	na	na	na	na	na	na	na
7	48%	370	A	A	A	A	A	A	A
8	8%	1,769	D	F	F	F	F	F	F
9	11%	1,382	C	D	D	D	D	D	D
10	7%	2,352	E	F	F	F	F	F	F
11	11%	1,986	D	F	F	F	F	F	F
12	12%	1,877	D	F	F	F	F	F	F

[a]Weighted percentage based on passenger car equivalence.

Note: pce=Passenger Car Equivalence; na= Not Applicable

Note: Values only reported for those potential platoon sites with at least 3 lanes in the westbound direction.

Note: Posted speed limit is 112 km/hr (70 mi/hr) at each platoon site.

Discussion

CAVs are expected to improve safety, congestion, emissions, and energy consumption and address the growing need for mobility in our transportation system. In proportion to the number of registered highway vehicles, heavy-duty vehicles consume a disproportionately high proportion of energy consumed by the transportation sector, which leads to high operating expenses for trucking companies. Platooning has the potential to provide significant fuel cost saving benefits and reduce HDV emissions by increasing the density of trucks on the road, which reduces the aerodynamic drag. This paper presents a method to determine viable platoon demonstration sites on highways. In particular, this paper identifies those five and six lane portions of the Pennsylvania Turnpike where a lane could be reserved for a platoon demonstration site and estimates how current LOS at these potential platoon sites could be impacted at different penetration rates, using the best available traffic information about the passenger cars and trucks traveling on this highway. The main dataset used for this paper was the Pennsylvania Turnpike's hourly traffic flow reports from May 1, 2017 to May 5, 2017, which contains vehicle class group level data of the traffic flow between interchanges for each hour of the day over the course of 5 days. For this paper the authors focus on commercial trucks since these vehicles drive for long distances along the same route, often concentrated in few corridors and could benefit greatly from platooning due to their low fuel efficiency.

In order to determine feasible testing areas on the Pennsylvania Turnpike the authors first identify those portions of the highway that have a total of five, 3 lanes in one directions, or six lanes, 3 lanes in both direction, for greater than 2 miles as it is not reasonable to dedicate a lane to platooning if there are only 2 lanes available and sections shorter than 2 miles provide are not long enough in length to hold a demonstration. There are a total of 12 sections on the Pennsylvania Turnpike where a platoon demonstration site could take place. Out of these 12 sites, six have three lanes in both directions and six have three lanes in only one direction. Seven are located in Western and Central Pennsylvania, collectively, while the remaining five are located in Eastern Pennsylvania near Philadelphia.

The results suggest that those five and six lane segments in Western and Central

Pennsylvania could be viable options for a platoon site demonstrations because these areas have relatively low peak hour traffic and a high proportion of vehicles traveling on these road segments are commercial trucks. The longest potential platoon demonstration site, platoon site 7, is located in Northern Franklin County, PA, between the Willow Hill and Blue Mountain Interchange, but has 3 lanes only in the westbound direction. This platoon site also has the lowest peak hour traffic flow rate and has the highest proportion of commercial truck traffic when compared to the other platoon sites, and operates at LOS A during peak hour traffic. This is the only site observed in the analysis that does not experience a decline in peak hour LOS from reserving a lane for platooning, regardless of the commercial truck platoon penetration rate. In the eastbound direction, the longest platoon site, platoon site 4, is about 9.5 miles in length and is located in Westmoreland County, between the Donegal and Somerset interchanges. There is a relatively high proportion of commercial trucks traveling on this platoon site during peak hour traffic. While the LOS does decline with the implementation of a platoon demonstration site, cars should still be able to travel with spacing between vehicles adequate enough to maintain a high level of physical and psychological comfort for motorists. Platoon sites 1 and 2 have three lanes in both directions and are about 6 and 7 miles in length, respectively. Platoon site 1 is located in Allegheny County, between the Warrendale and Butler Valley interchanges, while platoon site 2 is located in Westmoreland County between Irwin and New Stanton. The LOS are likely to decline these areas if a platoon lane is reserved but similarly to platoon site 4, vehicles should still be able to travel at reasonably free flow. There is a trade-off between safety and capacity so the Pennsylvania Turnpike may be willing to consider these section, since drivers will still be able to travel at free flow speeds and the likelihood of a crash between passenger cars and commercial trucks would decrease. The recommended platoon demonstration sites are shown in Table 8.

Table 8. Recommended Platoon Demonstration Sites on Pennsylvania Turnpike

Platoon Site #	No. Lanes	3 Lane Direction	County	Length (miles)	Eastbound Peak Hour Level of Service	%Commercial Trucks Eastbound[a]	Westbound Peak Hour Level of Service	%Commercial Trucks Westbound[a]
1	6	Both	Allegheny	6.2	B	16%	A	22%
2	6	Both	Westmoreland	7.3	A	12%	A	16%
3	5	East/North	Westmoreland	7.9	A	26%	NA	NA
4	5	East/North	Westmoreland	9.4	A	27%	NA	NA
5	5	West/South	Somerset	5	NA	NA	A	27%
6	5	East/North	Fulton	3.4	A	26%	NA	NA
7	5	West/South	Franklin	10.5	NA	NA	A	48%

[a]Weighted percentage based on passenger car equivalence.

Note: pce= Passenger Car Equivalence ; NA= Not Applicable

Note: Level of service only reported for those directions with 3 travel lanes

Although there are some viable options to launch a platoon demonstration site there are also areas of the Pennsylvania Turnpike where reserving a lane could have detrimental impacts on traffic flow and LOS. Platoon sites 8 through 12, all located in Montgomery County, PA, have a lower LOS than the other platoon sites and a very low proportion of vehicles traveling on these sections are commercial trucks. For example, at platoon site 8, 4 and 8 percent of vehicles traveling on this road segment during peak hour in the eastbound and westbound directions, respectively, are commercial trucks. If a lane is dedicated to platooning, there are not much trucks traveling in this direction and passenger cars are now limited to travel in two lanes, which could result in a constant traffic jam where vehicles traveling on these sections move in lockstep with the vehicle in front of it, with frequent slowing required. Regardless of the commercial truck platoon penetration rate, LOS during peak hour traffic remains at an F grade at these four sites and the only way to achieve a higher LOS would be to add another non-dedicated travel lane.

The platoon demonstration could be an on-road Level 2 automated truck demonstration pilot between commercial trucks that are connected by Vehicle to Vehicle (V2V) communications. The lead driver controls the acceleration and braking of all of the trucks in the platoon, while the drivers in the successive or trailing vehicles are present but aren't required actively to steer or control vehicle speed, but must remain alert at all times. The demonstration could be done in two separate phases. In phase one, there could be a dedicated lane for platoon demonstrations. In phase two, there will be no dedicated lane and all platoons will travel in mixed traffic situations. The purpose of both phases would be to identify any risks or hazards, conduct a before and after analysis on truck travel times, fuel consumption, and congestion, compare results between phases, and provide a smoother transition to CAV transportation. Data should be collected on vehicle speed and acceleration, brake pressure, and spacing between vehicles at both constant and varying lead vehicle speeds. For safety purposes, an operational design domain (ODD) (i.e., the specific conditions under which a given driving automation system or feature thereof is designed to function) should be defined. For example, pilot testing could be done during the daytime in clear weather conditions when lane markings are clearly visible. Artificial work zones (i.e. jersey barriers) could also be implemented into the pilot to assess traffic operations and safety. The Pennsylvania Turnpike should work together with local law enforcement to ensure that they are aware of any on-going testing and can respond appropriately and effectively in case of emergency. Some possible barriers to truck platooning are following distance requirements or "Following to close" laws, which restrict the lawful operation of tightly spaced platoons (State of Pennsylvania 2010).

Time of day and day of week restrictions could be considered when choosing a platoon demonstration site, to better ensure that the LOS on the turnpike is minimally impacted. In the eastbound direction, the highest traffic flow rates most commonly occur on Thursday and Fridays from the early afternoon to the early evening. In comparison, peak hour traffic usually occurs in the westbound direction on Mondays and Tuesdays in the morning to the early afternoon. Setting up platoon demonstrations on off-peak days and hours would provide trucks with potential fuel savings benefits, while still allowing all other vehicles to travel at or near free flow. The Pennsylvania Turnpike would also need to consider how to control access to these platoon lanes. Trucks with platooning capabilities entering the turnpike could be required to have a special E-ZPass that would provide it with access to the platoon lane, while keeping all other vehicles in their respective lanes. Non-commercial trucks or commercial trucks without platooning capabilities that decide to enter the platoon lane could be issued a ticket or fine using the E-ZPass system. Similarly to dedicated bus lanes, a dedicated platoon lane could provide numerous social and economic benefits. Dedicated platoon lanes separate commercial trucks from mixed traffic, allowing commercial trucks to travel more quickly through the turnpike. In addition, dedicated platoon lanes reduce interaction between commercial trucks and other vehicles, minimizing the risk for traffic crashes.

According to the 2013 Pennsylvania Department of Transportation Statewide crash dataset, there were about 1,500 crashes that occurred on the Pennsylvania Turnpike in 2013. Out of these 1,500 crashes about 240 or 17% of crashes involved at least one HDV, including 3 fatal and 88 injury crashes. According to the National Highway Safety Administration (NHTSA), the cost of a crash (Blincoe et al. 2015) is close to $154,000 in $2010. Because the crash data is from the year 2013, the Consumer Price Index (CPI) was used to find the total cost of a crash in 2013 dollars, which is approximately $163,700 or $47,400 in economic costs and $116,340 in quality-adjusted life years (QALYs) cost (Bureau of Labor Statistics 2018). This would result in an annual loss of about $39 million or $11 million in economic costs and $28 million in QALYs cost, from crashes involving heavy duty vehicles on the Pennsylvania Turnpike. Accommodating CAVs on the Pennsylvania Turnpike could aid in reducing the frequency and severity of crashes involving HDVs, which could result in economic benefits to households, public revenues, and private insurers. For example, if 25% of all HDV crashes on the Pennsylvania Turnpike were avoided, this would provide an annual benefit of about $10 million. If all HDV crashes could be avoided this would result in an upper bound annual benefit of about $39 million. Greater benefits could be realized as more roadways transition to CAV transportation. Automobile manufacturers and automated and connected vehicle technology companies are investing millions of dollars to make CAVs a reality. Policymakers, engineers, as well as Turnpike commissions should begin to consider ways how mixed-traffic could impact congestion, safety, energy use, and traffic operations so that there may be a smoother transition and minimize any negative consequences on the way CAV transportation.

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Notation

The following symbols are used in this paper:

$AV =$ is the commercial truck platoon penetration rate

$C_{East_i} =$ is the proportion of commercial trucks traveling during peak hour on platoon site i

$PC_{East_i} =$ is the eastbound peak hour passenger car traffic volume at platoon site i

$R =$ is the passenger car equivalent conversion factor trucks and buses for extended general highway segments on rolling terrains

$Trucks_{East_i} =$ is the number of light (>7,000 lbs.), medium, and heavy duty trucks traveling on platoon site i during peak hour traffic in the eastbound direction

$Vol_{East_i} =$ is the total eastbound peak hour traffic volume (pce/hr) at platoon site i

$Vol_{Platoon-East_i} =$ is the eastbound peak hour traffic volume (pce/hr) when there is a dedicated platoon lane at platoon site i

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