

## Article

# Estimation of Appropriate Acceleration Lane Length for Safe and Efficient Truck Platooning Operation on Freeway Merge Areas

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**Abstract:** The length of an acceleration lane is one of the dominant freeway geometric design parameters. This length requires new analyses to anticipate the needs of heavy commercial vehicle (HCV) platooning. We evaluated the safety and operational impact of HCV platooning on acceleration lane length for a freeway ramp in Ontario, Canada. This study modified the 2018 AASHTO's acceleration lane length estimation analytical model. Furthermore, this study used a VISSIM micro-simulation model and surrogated safety assessment model (SSAM) to examine the safety and operational impact on the real-world circumstances of HCV platooning at 0.6 s and 1.2 s headways and different market penetration rates of 0%, 5%, and 10%. The results suggest a minimum acceleration lane length of 600 m for platooned HCVs, which is inadequate compared to American and Canadian design guidelines. An extended acceleration lane length (600 m) will improve safety by reducing conflict by 19.2% and operational performance by reducing 3.9% of 85th percentile merging time for the operation of 5% HCV platooning with 0.6 s headway compared with 350 m acceleration lane length. This study suggests 5% of traffic containing two HCV platoons with 0.6 s headway may be reasonable for operation during certain hours of the day under existing conditions.

**Keywords:** truck platooning; acceleration lane length; micro-simulation; safety; mobility



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## 1. Introduction

Vehicles merging from an on-ramp to a freeway inevitably create complex lane changing interactions resulting in operational and safety challenges such as travel delays and collisions. Collisions on freeway merge areas associated with on-ramps are a significant issue. Zhang [1], for example, investigated three years of collisions from 2010 to 2012 on 60 different interchanges in Missouri, United States. The study examined 844 collisions and identified 96 (11%) occurred along freeway on-ramps. Acceleration lanes in merge areas are designed to improve safety for vehicles merging in these areas [2,3], but it is necessary to consider the appropriate length for the safe and efficient operation of truck platoons emerging on our roadways.

### 1.1. Acceleration Lane

The American Association of State Highway and Transportation Officials (AASHTO) (2018) guideline identifies an acceleration lane on a freeway merge area as a speed change lane for vehicles traveling from an on-ramp to the mainline freeway. Two common designs for the acceleration lane include parallel and taper styles with the former parallel design suggested for heavy commercial vehicle (HCV) operations [2,3]. Vehicles use the acceleration lane to accelerate to a target speed before merging into the mainline freeway traffic. The methodology used to estimate acceleration lane length was first discussed in AASHTO (1965) [4] with a minimum length required for an acceleration lane and remained same in AASHTO (2018) [3], which was 1200 ft (360 m) including a 300 ft taper section. The taper section refers to the end of the merging ramp where the width of the travelling lane is gradually reduced.

Past studies have noted that vehicle length and acceleration rate are key factors contributing to the determination of the length of acceleration lanes [5–15]. Reilly et al. [15] discussed the relationship between vehicle length and acceleration lane length and showed that longer vehicles require more time, as well as a subsequently longer acceleration lane length, to find an acceptable gap when merging into the mainline freeway.

Although many studies have shown that the length of HCVs affects driving behaviour, including lane changing behaviour on freeways [12,16,17], the acceleration lane length in existing geometric design guidelines was estimated by considering merging maneuvers between passenger vehicles and is expected to be much shorter than the length required to accommodate HCVs [15]. Using HCV speed profile data collected in the United States, Harwood et al. [6] recommended that acceleration lane length for HCVs should be longer by 95 ft, or 1.5 times the length given in the AASHTO (2018) design guideline. Qi et al. [12] developed an analytical model calibrated using the observed time gap required for HCVs to change lane. They also suggested that the AASHTO acceleration lane length was too short for HCV operation and proposed a much longer acceleration lane length. For example, Qi et al. [12] suggested that the acceleration lane for merging should be 1692 ft instead of 1200 ft suggested in AASHTO [3] design guideline for a freeway with 1100 vph, a design speed of 60 mph speed limit on the freeway, and a design speed of 30 mph on the ramp. Bareket and Fancher [14] recommended adding 300 ft with AASHTO's recommended acceleration lane length for ramp roadways with frequent long-combination vehicles (LCVs). An LCV is a tractor-trailer combination with two or more trailers attached to a single tractor.

The literature identifies the critical time gap as another major factor when determining acceleration lane length [7,12,15,18,19]. The critical time gap indicates the minimum gap between vehicles on the freeway that is acceptable for on-ramp vehicles to safely complete the merging maneuver. The field observations of Qi et al. [12] found that the critical time gap was 2.58 s for passenger vehicles and 3.06 s for HCVs. A longer critical time gap for HCVs influences the acceleration lane length design since a greater distance enables greater opportunities for the gap to be encountered by the merging vehicle.

There are no studies found to estimate a suitable acceleration lane length for HCV platooning. An HCV platoon consists of two or more HCVs in a convoy connected wirelessly by advanced vehicle-to-vehicle (V2V) communication technologies. Depending on the level of human control, an HCV platoon can be an example of connected autonomous vehicles (CAVs). The amount of technological control on the vehicles can vary as per the levels of driving automation defined by the Society of Automotive Engineers (SAE) [20]. An autonomous HCV platoon at SAE Level 3 (hereafter, Level 3) needs human drivers in all vehicles involved in the platoon. An HCV Platoon at SAE Level 4 (hereafter, Level 4) requires human driver involvement for the lead HCV but not the following HCV. An HCV platoon at SAE Level 5 (hereafter, Level 5) does not require a human driver for the lead HCV or following HCV.

In SAE Level 4, for instance, automation reduces or eliminates human driver involvement from one or more of the HCVs in the platoon [21,22]. As the length of an HCV platoon can be even longer than the length of an LCV, HCV platoons require particular consideration in merging areas to ensure safe and efficient transition from ramps to freeways. The review of past studies suggests that freeway merging areas may experience additional challenges due to the operation of Level 4 HCV platooning [23–28].

### *1.2. Heavy Commercial Vehicle Platooning*

Many studies have reported reductions in fuel consumption, usually between 6% and 10%, as a primary benefit of HCV platooning [29–34]. However, some logistics companies in North America prioritize the benefits of HCV platooning to overcome the driver shortage and reduce labour costs. Since 2018, FPIInnovations, for example, has tested Level 5 HCV platooning, with no human drivers required, for the forestry industry where severe driver shortages can be found in remote locations. The platoons transport timber from forests to a nearby port [35].

Level 3 HCV platooning requires human drivers in all the HCVs but provides flexibility when engaging and disengaging HCVs in a convoy. Level 4 or Level 5 HCV platooning is considered less flexible than Level 3 and may not easily allow other vehicles to cut-in and cut-out of an HCV platoon. One reason for the lack of flexibility is the need to maintain proximate distance between the HCVs for the whole journey from origin to destination to maintain a consistent and stable wireless connection between the lead HCV and the following HCVs. The close distance creates a challenge for Level 4 and Level 5 HCV platooning when the vehicles attempt to merge into a mainline freeway together. It is anticipated that a longer acceleration length will be needed for the platooning vehicles to find an appropriate time gap that allows two or more HCVs to make a simultaneous lane change.

Many studies have examined the operational benefits and challenges of HCV platooning, but these studies were based mainly on simulations or field tests on freeway sections. The studies assumed that each HCV in a platoon can always engage or disengage as required by the traffic and vehicles cutting-in and cutting-out. The studies therefore assumed Level 3 automation and did not consider the impact of HCV platooning with one of more driverless HCVs. Ramezani et al. [34], for instance, considered a maximum of five HCVs in a platoon on a freeway and assumed that any HCV in the platoon could easily leave or re-join the platoon during the entire travel whenever needed. Such studies did not consider Level 4 or Level 5.

The market penetration rate refers to the proportion of platooned vehicles as a percentage of the number of HCVs using the road [36], i.e., the percentage of HCVs operating as a platoon. Few studies have considered the operational level impact of the market penetration rate of platooned HCVs on the mobility and safety of traffic flows, and these studies typically rely on simulations. Gordon and Turochy [37] reported that a 20% market penetration of HCV platooning can reduce travel time delay by 40% travel time (7.7 s per vehicle) on average for both passenger vehicles and HCVs when compared to no platooning average travel time delay 19.1 s per vehicle. The study simulated operations on 5.3 miles of Interstate Highway (I-85) in Alabama. Other studies, however, have reported that an HCV market penetration rate of more than 25% can increase travel time and result in delays and additional conflicts that introduce safety issues, especially on freeway merging areas [23–25]. To reduce delays and address the concerns for HCV platooning, Arnold and Roorda [25] suggested providing an additional 50 metres of acceleration lane to the distance recommended by the AASHTO (2018) [3] Design Guideline.

### 1.3. Study Goal and Objectives

The goal of this study was to investigate the operational level impact of Level 4 HCV platooning on freeway parallel-type merge areas in terms of safety and mobility. The study has two objectives:

1. Improve an existing analytical model (hereafter, AASHTO (2018) recommended acceleration lane length model) to estimate the acceleration lane length required for safe and efficient operation of Level 4 HCV platooning on freeway merging areas near on-ramps; and
2. Evaluate the operational impact of Level 4 HCV platooning market penetration rates (0%, 5%, and 10%) on the safety and mobility of traffic at freeway merge areas near on-ramps.

For objective 1, we modified an existing analytical model to reflect the total length of platooned HCVs. The total length of an HCV platoon can vary depending on the length of the different HCVs and the physical gap between two consecutive HCVs. Section 3 discusses these issues.

For objective 2, we assumed relatively low market penetration rates of 0%, 5%, and 10% as it is uncertain when, or if, a substantially higher market penetration rate would be realistic. Despite the expectation that some levels of platooning using advanced V2V technologies will eventually be applied on public roads, we consider it unlikely that Level 4

HCV platooning at a market penetration rate higher than 10% will be widespread in the near future.

Like previous studies [23–26,37–40], this study undertook the simulation by developing a set of micro-simulation models using PTV Vissim. The US FHWA Surrogate Safety Assessment Model (SSAM) is used to assess the safety performance of platooned HCVs on freeway merge areas [41,42].

Section 2 describes the study area and study data. Section 3 discusses the estimation of acceleration lane length using the analytical models specified in the 2018 AASHTO design guidelines. Section 4 explains the simulation models. Section 5 presents and discusses the results of the analytical and simulation models. Section 6 presents the conclusions and recommendations.

## 2. Study Area and Data Descriptions

Merging maneuvers are affected by freeway and ramp traffic and the freeway and ramp design speed [12,15]. To determine appropriate merging segment acceleration lane length using an analytical or simulation model, it is necessary to know freeway and merging ramp traffic volumes, the percentage of vehicles by classification, the right-most lane traffic distribution factor (the closest lane on the freeway where number of traffic flow will be directly interrupted with merging ramp traffic), and vehicle acceleration rates.

Figure 1 shows the study interchange on Highway 400 in Vaughan, Ontario, Canada. The blue star denotes the study location on Highway 400. The blue line indicates a northbound freeway (Highway 400), and the green line refers to a ramp roadway connecting Teston Road to Highway 400. A 23 km segment of northbound Highway 400 in Ontario, Canada, was selected for this study. The selected segment includes a northbound merging ramp at the Teston Road partial cloverleaf interchange. The posted speed limits are 100 km/h on the freeway. The Teston Road northbound merging ramp is a single lane with a 350 m acceleration lane including a 90 m taper section and merging traffic from Teston Road to the five lanes of Highway 400. The posted speed limits are 50 km/h on the ramps. The acceleration lane was constructed according to Transportation Association of Canada (TAC) (2017) geometric design guidelines [2] and AASHTO (2018) geometric design guidelines [3].

Traffic and speed data were obtained from the Ontario Ministry of Transportation (MTO) for a week between 28 October 2018 and 4 November 2018. The traffic volume dataset provided 24 h hourly traffic volumes for the freeway and merging ramp, including the number of passenger vehicles and different categories of HCVs (i.e., single-unit HCV, LCV, etc.).

For the same week, map data were obtained from the American Transportation Research Institute (ATRI) via MTO [43] and from HERE [44]. These data provided travel speed information derived from anonymous GPS tracking for passenger vehicles and HCVs for each lane of the freeway.

The MTO traffic data showed that, from 1:00 p.m. to 2:00 p.m., an average of 6100 vehicles used the freeway and an average of 1100 vehicles used the Teston Road merging on-ramp. The freeway traffic composition included 88.2% passenger vehicles, 11.2% HCVs, and 0.6% LCVs. The on-ramp traffic consisted of 93.8% passenger vehicles, 4.7% HCVs, and 1.5% LCVs [45].

From the start of the ramp to the start of the acceleration lane (i.e., the gore-point), the average passenger vehicle and HCV travel times were identical in the MTO data and the map data: both passenger vehicles and HCVs travelled the distance in 66 s. The traffic volume and speed data profile were used as inputs for the analytical and simulation models to analyse, calibrate, and validate the models.



Figure 1. Study interchange on Highway 400 in Vaughan, Ontario, Canada.

### 3. Estimation of Acceleration Lane Length Using Analytical Models

This section discusses the estimation of acceleration lane length using the analytical models specified by AASHTO (2018) and TAC (2017) [2,3] by Qi et al. [12], as well as by the National Cooperative Highway Research Program (NCHRP). The Qi et al. model is known as the 2019 Center for Advanced Multimodal Mobility Solutions and Education (CAMMSE) model, and the NCHRP model is known as the NCHRP 3-35 Model.

The AASHTO (2018) and TAC (2017) guidelines used passenger vehicle acceleration rates to compute acceleration lane length [2,3]. Neither set of guidelines took HCV or HCV platooning operations into account when calculating the acceleration lane length required for a merging a passenger vehicle. The AASHTO guidelines also recognized that HCVs and buses have slow acceleration rates compared with passenger vehicles, and therefore need longer acceleration lanes, but did not consider the critical time gap which is directly associated with vehicle length. Lee [9] suggested that total accepted gap can be calculated using Equation (1):

$$\text{Total Accepted Gap} = C_{nt}^{\text{lead}, cr} + L_i + C_{nt}^{\text{lag}, cr} \quad (1)$$

where

$C_{nt}^{\text{lead}, cr}$  = lead critical gap (m) of  $n$  individuals at time  $t$ ;  
 $C_{nt}^{\text{lag}, cr}$  = lag critical gap (m) of  $n$  individuals at time  $t$ ; and  
 $L_i$  = length of merging vehicle  $I$  (m).

### 3.1. AASHTO Model

The recent 2018 AASHTO model was first referenced in the 1965 AASHTO guidelines [3,4]. The model is shown in Equation (2):

$$A = \frac{(1.47V_m)^2 - (1.47V_r)^2}{2a} \quad (2)$$

where

$A$  = acceleration length (ft);  
 $V_m$  = freeway design speed (mph);  
 $V_r$  = ramp design speed (mph); and  
 $a$  = acceleration rate (ft/s<sup>2</sup>).

### 3.2. CAMMSE Model

Qi et al. [12] suggested the CAMMSE model, a new analytical model that included traffic volume and HCV operations. According to the CAMMSE model, the acceleration lane length represents the summation of acceleration ( $L_1$ ) and gap searching segment ( $L_2$ ). The CAMMSE model is shown in Equations (3)–(5). Equation (3) is used to estimate acceleration lane length:

$$L = L_1 + L_2 \quad (3)$$

where

$L$  = total acceleration lane length (ft);  
 $L_1$  = acceleration segment length (ft); and  
 $L_2$  = gap searching length (ft).

The  $L_1$  and  $L_2$  length components can be calculated as follows:

$$L_1 = \frac{(1.47V_m)^2 - (1.47V_r)^2}{2a} \quad (4)$$

$$L_2 = V_m d \quad (5)$$

$$d = \frac{e^{qT} - qT - 1}{q(1 - e^{-qT})} \quad (6)$$

where

$T$  = critical time gap (s);  
 $d$  = gap searching time or merging delay (s); and  
 $q$  = average freeway traffic volume (vps/ln).

The CAMMSE model also considered the maximum distance from merging ahead ( $V_m + 5$  mph) and merging behind ( $V_m - 5$  mph) conditions, as shown in Equation (7), where subscripts (a) and (b) denote merging ahead and merging behind, respectively:

$$L = \text{Max}(L_a, L_b) \quad (7)$$

When determining gap searching length, the CAMMSE model considered only merging ramp traffic volume. Merging delay ( $d$ ) was estimated by field observations of passenger vehicles and HCVs. However, for a safe merging maneuver, the gap must be accepted, and gap acceptance is dominated by freeway right-most lane traffic volume, which is also indicated by Greenshields et al. [46] and Reilly et al. [15].

### 3.3. NCHRP 3-35 Model

The NCHRP 3-35 model was generated by Reilly et al. [15]. Reilly et al. [15] considered acceleration ( $L_1$ ) and gap searching segment ( $L_2$ ) when estimating acceleration lane length. Reilly et al. [15] suggested Equation (8) for estimating the gap searching length ( $L_2$ ) including gap acceptance zone:

$$L_2 = L_{AP} + d_{hr} \quad (8)$$

where

$L_2$  = gap searching length acceptance for safe merging;

$d_{hr}$  = distance required to search and accept a headway gap including delay due to ramp vehicle (ft); and

$L_{AP}$  = length of the ramp vehicle's adjust position zone (ft), in the event when ramp vehicle needs to reject the initial lag gap and modify its relative position on the basis of the speed of freeway right-most lane vehicle.

The adjust position length  $L_{AP}$  can be calculated as follows:

$$L_{AP} = v_{rm1}t + \frac{a_1}{2}t^2 \quad (9)$$

$$t = \frac{2(\Delta d)}{\Delta v + \sqrt{(\Delta v)^2 + 2(\Delta a)(\Delta d)}} \quad (10)$$

where

$t$  = ramp vehicle time to collide with freeway right-most lane's lag vehicle (s);

$\Delta d$  = difference between absolute distances travelled by the freeway and ramp vehicles during the vehicle adjustment process (ft);

$\Delta v$  = speed differential between freeway right-most lane and ramp vehicles at the start of gap searching and gap acceptance zone (ft/s); and

$\Delta a$  = difference in acceleration rates of ramp and lag vehicle in freeway right-most lane at the end of acceleration segment (ft/s<sup>2</sup>).

Equation (10) can be re-written as follows:

$$t = \frac{2(\alpha v_f + L_i)}{(v_f - v_{rm1}) + \sqrt{\left((v_f - v_{rm1})^2 + 2(a_f - a_{rm})(\alpha v_f + L_i)\right)}} \quad (11)$$

where

$\alpha$  = car following constant (s);

$v_{rm1}$  = speed of ramp vehicle at the starting of gap searching lane/speed of ramp vehicle at the end of accelerating section (ft/s);

$a_{rm}$  = average acceleration rate of ramp vehicle at the starting of gap searching lane/at the end of accelerating section (ft/s<sup>2</sup>);

$a_f$  = average acceleration rate of freeway right most lane vehicle (ft/s<sup>2</sup>); and

$L_i$  = length of merging vehicle such as a passenger vehicle or an HCV (ft).

In Equation (8), the distance required to search and accept a headway gap including delay due to ramp vehicle can be estimated as follows:

$$d_{hr} = \frac{d_q}{d_s} d_h \quad (12)$$

where

$d_h$  = distance required searching for and accepting a gap without effect of ramp volume (ft);

$d_s$  = average traffic delay to a merging vehicle (s); and

$d_q$  = average traffic delay to a merging vehicle with ramp volume effect (s).

$$\frac{d_q}{d_s} = \frac{B + \frac{\sigma^2 + (B)^2}{2\left(\frac{1}{p} - B\right)}}{B} \quad (13)$$

In Equation (13),  $B$  and  $d_h$  can be written as follows:

$$B = \frac{1}{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)} \left( e^{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T} - \left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T - 1 \right) \quad (14)$$

$$d_h = \frac{v_{rm}}{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)^2} \left( e^{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T} - \left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T - 1 \right) \quad (15)$$

where

- $k$  = right-lane distribution factor;
- $v_f$  = freeway speed (ft/s);
- $v_{rm}$  = ramp design speed (ft/s);
- $p$  = ramp volume (vps);
- $\sigma^2$  = variance of time spent in a queue (s<sup>2</sup>);
- $\lambda$  = volume in right lane (vps);
- $N$  = number of freeway lanes;
- $q$  = total freeway volume (vph); and
- $T$  = acceptable time headway (s)

### 3.4. Proposed Model

In this paper, we propose an analytical model that can estimate an appropriate acceleration lane length for efficient and safe truck platooning operations. The proposed model adapts the 2018 AASHTO, CAMMSE, and NCHRP 3-35 models, and includes acceptable gap searching length. The proposed model also considers the length of HCVs ( $L_i$ ), the number of HCVs in a platoon ( $n$ ), and the physical distance between HCVs ( $d$ ). No previous research has considered the latter two variables. The model can also be used to estimate the acceleration lane length required for LCVs.

The accepted gap equation from Lee [9] did not consider the number of platooned HCVs or the physical distance between HCVs, and therefore we propose the use of Equation (16) instead of Equation (1) to incorporate the number of HCVs in a platoon ( $n$ ), the physical distance between HCVs ( $d$ ), and the length of HCVs ( $L_i$ ) to estimate total accepted gap for HCV platooning.

$$\text{Total Accepted Gap} = G_{nt}^{lead, cr} + (nL_i + (n - 1)d) + G_{nt}^{lag, cr} \quad (16)$$

Furthermore, Equation (17) can be used to replace Equation (11):

$$t = \frac{2\left(\alpha v_f + (nL_i + (n - 1)d)\right)}{\left(v_f - v_{rm1}\right) + \sqrt{\left(\left(v_f - v_{rm1}\right)^2 + 2\left(a_f - a_{rm}\right)\left(\alpha v_f + (nL_i + (n - 1)d)\right)\right)}} \quad (17)$$

In both Equations (16) and (17):

- $n$  = number of vehicles in a platoon;
- $L_i$  = length of merging vehicle, i.e., an HCV or an LCV or passenger vehicle (ft); and
- $d$  = physical gap between platoon vehicles (zero for single vehicle) (ft).

As suggested by Qi et al. [12], regarding the merging ahead condition, the proposed model uses  $V_h$  instead of  $V_m$  in Equation (4), where  $V_h = V_m + 5\text{mph}$ . Acceleration segment length can be estimated, as shown in Equation (18).

$$L_1 = \frac{(1.47V_h)^2 - (1.47V_r)^2}{2a} \quad (18)$$

Since field observed gap searching time is not still available for HCV platooning, we therefore propose the use of Equation (8) instead of Equation (5) to estimate gap searching length and the use of Equation (16) as a replacement of Equation (11). By summing proposed acceleration segment length and gap searching length equations, the required acceleration lane length can be calculated.

### 3.5. Estimation of Acceleration Lane Length Using Analytical Model

We used the proposed analytical model to estimate the acceleration lane length required for passenger vehicles and WB-20 HCVs. We based our estimation on the observed freeway traffic volume of 6100 vph and the observed ramp volume of 1100 vph (see Section 2). For passenger vehicles, we used the acceleration rate suggested in AASHTO (2018) [3], and for WB-20 HCVs, we used the acceleration rate suggested for HCVs by Torbic et al. [8].

We compared the estimated critical time gap with the field observations of Qi et al. [12] before using this result for the calculation of acceleration lane length. A two-sample *t*-test was used for passenger vehicles and for WB-20 HCVs. The null hypothesis was that the estimated and observed critical time gaps were equal [47].

Table 1 shows the *t*-test results for the critical time gap. The results show that the null hypothesis cannot be rejected, i.e., the differences were not statistically significant at the 95% confidence level (*p*-value > 0.05) and the observed and estimated time gaps could be considered close enough.

**Table 1.** *t*-test results for critical time gap.

Vehicle Classification	Estimated Time Gap (s)	Observed Critical Time Gap (s) (Qi et al., 2019) [12]	<i>t</i> -Test	<i>p</i> -Value
Passenger vehicle	2.60	2.58	0.89	0.44
WB-20 HCV	3.07	3.06	1.41	0.25

Next, we compared the acceleration lane lengths given by the CAMMSE and 2018 AASHTO models with the acceleration lane lengths estimated by the proposed models. The comparisons were undertaken for ramp design speeds of 65 km/h and 81 km/h, and for a freeway speed of 105 km/h. The absolute differences between the acceleration lane lengths estimated by the established models (CAMMSE and 2018 AASHTO models) and our proposed model were less than 5%. We used a two-sample *t*-test for the statistical comparison. The null hypothesis was that the estimated acceleration lane length for ramp design speed 81 km/h was equal to both CAMMSE and 2018 AASHTO acceleration lane length. Table A1 shows the *t*-test results for acceleration lane length according to the CAMMSE and 2018 AASHTO models. The *t*-test results indicated that we cannot reject the null hypothesis because the *p*-value at the 95% confidence level was greater than 0.05. These results suggest that it is reasonable to use the proposed model to estimate the acceleration lane length required for HCV platoons to merge onto the mainline freeway.

The AASHTO (2018) guidelines recommend allowing at least 360 m for an acceleration lane without taper-section [3]. The TAC (2017) guidelines recommend allowing 350 m an acceleration lane with parallel-type merging, regardless of the ramp design speed or freeway speed [2]. The AASHTO guidelines also recommend a maximum length of 610 m for an acceleration lane only when a vehicle's speed at the beginning of the ramp is zero, freeway speed is 130 km/h, and ramp design speed is 92 km/h.

Our estimation of the acceleration lane length required for HCV platooning was based on platoons of two WB-20 HCVs with each vehicle length equal to 22.70 m. Ramezani et al. [34] reported 0.6 s and 1.2 s between two consecutive HCVs as the two most stable headways that HCVs can maintain while they are travelling in a convoy. Therefore, these two headway values were selected in this study for further analyses: 0.6 s (HCVP\_0.6H; 58.84 m) and 1.2 s (HCVP\_1.2H; 72.28 m) [34,48–50]. Here, HCVP\_0.6H refers to two

HCV platooning connected with 0.6 s headway, and the overall length including physical gap between platoon HCVs was 58.84 m. Similarly, HCVP\_1.2H demonstrates two HCV platooning connected with 1.2 s headway, and the overall length was 72.28 m. We also considered eight ramp design speeds (from 49 to 102 km/h) and seven average running speeds (from 44 to 81 km/h) at the start of the ramp. Vehicles that started on the ramp with a speed that was equal to or more than the ramp design speed were not required to accelerate while on the ramp.

Table 2 shows the acceleration lane lengths estimated by the proposed model.

**Table 2.** Estimates of acceleration lane length for two platooning WB-20 HCVs.

Freeway Speed, $V_f$ (km/h)	Ramp Design Speed, $V_r$ (km/h)	Average Running Speed at the Beginning of Ramp (km/h)						
		44	50	57	63	70	76	81
<i>Required Acceleration Lane Length (m)—2 HCV Platooning 0.6 s Headway</i>								
105	49	390						
105	57	365	420					
105	65	340	395	405				
105	73	310	370	390	450			
105	81	275	325	350	410	480	585	
105	89	235	280	305	360	430	490	630
105	92	215	260	285	335	405	500	605
105	102	155	190	215	260	320	400	490
<i>Required Acceleration Lane Length (m)—2 HCV Platooning 1.2 s Headway</i>								
105	49	400						
105	57	375	430					
105	65	350	405	420				
105	73	320	385	405	470			
105	81	285	340	370	430	510	620	
105	89	245	295	325	380	455	545	685
105	92	230	275	305	360	435	540	660
105	102	170	205	240	285	350	445	545

Table 2 shows the following:

- HCV platoons with a longer headway (1.2 s) required a longer acceleration lane than HCV platoons with a shorter headway (0.6 s); and
- The longest acceleration lane length estimated was 685 m for a platoon with a headway of 1.2 s traveling at 81 km/h at the start of the ramp with a ramp design speed of 89 km/h.

If we compare the results in Table 2 (calculated acceleration lane length for HCV platooning) with 2018 AASHTO and 2017 TAC suggested acceleration lane length (on the basis of passenger vehicle merging maneuverers), we find that

- Our model's longest acceleration lane length estimate (685 m) was approximately 75 m longer than the 2018 AASHTO maximum recommended acceleration lane length. This difference is particularly striking as our model was estimated for platooned HCVs merging onto a freeway with a 25 km/h lower speed than the 2018 AASHTO speed. Furthermore, the estimated acceleration lane was 325 m longer than the 2018 AASHTO's minimum recommended value.
- The acceleration lane recommended by 2017 TAC was about 350 m [2], i.e., considerably less than many of our estimates and 335 m less than our highest estimate of 685 m.
- As stated in the 2018 AASHTO and the 2017 TAC, the minimum acceleration lane length was defined as the 85th percentile of vehicles merging onto the freeway in the provided acceleration lane to meet the desired freeway speed. This resulted in some acceleration lane lengths in 2018 AASHTO and the 2017 TAC that were smaller than their stated minimum values. Our model also estimated some acceleration lane lengths that were shorter than the minimum values given in the 2018 AASHTO (360 m) and the 2017 TAC (350 m). For example, for a platoon with a headway of 1.2 s travelling

on a ramp with a design speed of 102 km/h (63 mph), the acceleration lane length estimated by our proposed model was less than the minimum values given in both North American design guidelines. This was primarily caused by some platooned HCVs on the ramp roadway having already reached a 102 km/h (63 mph) speed prior to matching the freeway's 105 km/h (65 mph) speed. By contrast, it will take a longer distance for platooned HCVs accelerating from a slow-speed ramp, i.e., 57 km/h (35 mph), to reach the freeway 105 km/h (65 mph) speed.

- The estimated acceleration lane length for platooned HCVs for our proposed model was always longer than the suggested value for the different speed ramp roadways in the design guidelines. This was due to the gap searching length that was not considered in either the 2018 AASHTO or 2017 TAC.
- Regardless of ramp speed, the acceleration lane length estimated by our proposed model for merging passenger vehicles was about half the length required for merging HCV platoons travelling with a headway of 1.2 s.
- The 2017 TAC recommended acceleration lane lengths were also noticeably shorter than those estimated by our model. For instance, in platooned HCVs with a headway of 1.2 s travelling through a ramp of 57 km/h (35 mph) speed, our estimated acceleration lane length was longer than the 350 m minimum stated in the 2017 TAC. In this circumstance, platooned HCVs needed to accelerate to 105 km/h (65 mph) in the acceleration lane and find a suitable gap to merge onto the freeways. The acceleration segment length and gap searching length factors led to the necessity for a longer acceleration lane length than the 2017 TAC minimum value.

Except for situations when HCV platooning are merging onto high-speed ramp roadways, our proposed model suggests that the acceleration lane length for an HCV platoon is longer than the minimum acceleration lane lengths recommended in the 2018 AASHTO and 2017 TAC. The acceleration lane lengths suggested by 2018 AASHTO and 2017 TAC were not sufficient for the HCV platoons investigated in this study, regardless of the speed on the ramp. Due to the inadequacy of acceleration lane length for merging HCV platoons, the platoons may experience significant delay and pose a safety risk. This issue has been reported in simulation-based studies such as those of Arnold and Roorda [25], Kuijpers [23], Maarseveen [38], and Wang et al. [24]. For an HCV platoon to travel uninterrupted on the ramp and merge onto a 105 km/h freeway, the analytical model's findings suggest that the acceleration lane should be 600 m long rather than the 360 m recommended by 2018 AASHTO and the 350 m recommended by 2017 TAC.

Analytical models provide an approach that can quickly generate results. However, this expediency comes at the cost of simplifying assumptions and ignores the stochastic nature of vehicle-to-vehicle interactions. Section 4 continues the investigation using a micro-simulation model.

#### 4. A Micro-Simulation Model to Estimate Acceleration Lane Length

The literature recommends micro-simulation modelling for detailed study of acceleration lane performance [23–25,38]. This section discusses the development of the micro-simulation model followed by calibration. Section 5 presents the results of the micro-simulation modelling.

##### 4.1. Model Development

The Base Model was developed to replicate current real-world traffic flow conditions and variability. The model required data on freeway traffic volume, merging ramp traffic, traffic composition (vehicle type and proportion of HCVs), infrastructure (acceleration lane length, etc.), and regulatory data (speed limits). We used data collected from Ontario highways for hourly traffic volumes for freeways and ramps, travel speeds, and travel times.

The development of the model relied heavily on car-following and lane-changing behavior. For freeway and autonomous vehicle modelling, we used the Wiedemann 99 (W99) car following model and lane changing model [51–53]. The values for the acceleration

and deceleration of passenger vehicles and HCVs were assigned in accordance with the ITE Handbook [6,54]. This section discusses two important issues including the input parameters and model calibration.

#### 4.1.1. Input Parameters

To simulate existing traffic conditions, we specified explicit driving behavior criteria for each vehicle type. As LCV and HCV features are comparable except for vehicle length, LCV driving behavior was characterised as HCV driving behavior. To simulate HCV platooning, we used the PTV COM interface and python programming [52,55]. Table 3 shows the input parameters for passenger vehicles, HCVs, and HCV platooning.

**Table 3.** Simulation input parameters.

Input Parameters	Wiedemann 99 (W99) Car Following Model			
	Default	Passenger Vehicles	HCVs <sup>2</sup> or LCVs <sup>3</sup>	HCV Platooning
Maximum look ahead distance (m)	250	250	250	300
Maximum look back distance (m)	150	150	150	300
Number of interaction objects	2	1	1	3
Number of interaction vehicles	99	1	1	2
Standstill distance (m) for following passenger vehicle	1.5	1.5	3.77	3.77
Standstill distance (m) for following HCV or HCV platooning	1.5	3.05	3.37	3.37
Standstill distance (m) for following HCV in Platoon	1.5	NA <sup>1</sup>	NA <sup>1</sup>	1
Time headway (s) for following passenger vehicle	0.9	1.8	1.84	1.84
Time headway (s) for following HCV or an HCV platoon	0.9	2.39	1.84	NA <sup>1</sup>
Time headway (s) between HCVs in platoon	0.9	NA <sup>1</sup>	NA <sup>1</sup>	0.6/ 1.2
Following distance oscillation (m)	4	4	14	14
Negative speed difference (m/s)	−0.35	−1.65	−2.07	−2.07
Positive speed difference (m/s)	0.35	1.65	2.07	2.07
Oscillation acceleration (m/s <sup>2</sup> )	0.25	0.09	0.097	0.097
Acceleration from standstill (m/s <sup>2</sup> )	3.5	0.5	0.3	0.3
Acceleration at 80 km/h (m/s <sup>2</sup> )	1.5	0.45	0.25	0.25
			Lane Changing Model	
Maximum deceleration (m/s <sup>2</sup> )	−3	−3	−1.62	−1.62
Safety distance reduction factor	0.6	0.6	0.6	1

<sup>1</sup> Note: NA indicates a value is not applicable. <sup>2</sup> HCV indicates the heavy commercial vehicle (WB-20 HCVs).

<sup>3</sup> LCV indicates a long combination vehicle.

The input parameters are discussed below:

- The “maximum look ahead distance” and “maximum look back distance” are the farthest distance a driver may view in front and behind in order to notice the surrounding traffic. The maximum look ahead and look back distances for passenger vehicles and HCVs were assigned in accordance with PTV’s [52] recommendations. As Level 4 HCV platooning allows HCVs to communicate up to a distance of about 300 m [55–57], we used 300 m the maximum look head and look back distance for HCV platooning. This distance allows platooning vehicles to examine the freeway’s right-most lane and determine whether the gap available is adequate.
- “Number of interaction objects” refers to the interaction of a vehicle with a variety of objects including traffic signals and other vehicles. The “number of interaction vehicles” refers only to interaction with other vehicles. Because passenger vehicles and HCVs have human drivers, the number of interaction objects and the number of interaction vehicles are defined as one for passenger vehicles and HCVs as recommended by PTV [52]. As HCV platoons can communicate with HCVs within the same platoon, the number of interaction vehicles and the number of interaction objects is defined as greater than one [58].
- The “standstill distance for following passenger vehicle”, “standstill distance for following HCV or HCV platooning”, and “standstill distance for following HCV

in a platoon” indicate the minimum desired distance needed to avoid a collision between a leading and following vehicle. For the standstill distances for following passenger vehicles, we used the distances suggested by Lu et al. [59] for passenger vehicles, HCVs, and HCV platoons. For the standstill distance for an HCV platoon following an HCV platoon, we used the distance suggested by Deng [60] and Deng and Boughout [61].

- The “time headway” refers to distance from the front of the lead vehicle or object to the front of the following vehicle and is additional to the standstill distance. As in previous studies, we assigned two different time headways (0.6 s and 1.2 s) to HCVs in a platoon [34,49,50].
- The “following distance oscillation (m)” indicates the maximum additional distance that a following vehicle driver can accept in addition to the desired safety distance. We used the observed following distance oscillation for HCVs and for HCV platoons developed by Durrani et al. [62].
- The “negative speed difference” refers to the relatively lower (negative) speed a following vehicle driver may adopt compared to the lead vehicle’s slower speed, and the “positive speed difference” refers to the relatively higher (positive) speed a following vehicle driver may adopt compared to the lead vehicle’s faster speed. We used the values suggested by Durrani et al. [62].
- “Oscillation acceleration” refers to the minimum acceleration/deceleration rate of the following vehicle while one vehicle is following another one in front it. We used the values suggested by Durrani et al. [62].
- “Acceleration from standstill” refers to the acceleration rate of a following vehicle (i.e., a passenger vehicle, an HCV, or an HCV platoon) from a standstill. “Acceleration at 80 km/h” refers to the acceleration rate of a following vehicle traveling at 80 km/h. We used the values suggested by Durrani et al. [62].
- In the lane changing model, “maximum deceleration rate for cooperative braking” refers to the rate at which a target vehicle needs to decelerate in order to allow another vehicle to perform a lane change and enter the target vehicle’s lane. We used the values suggested by Harwood et al. [6].
- The “safety distance reduction factor” indicates when a lead vehicle initiates a lane changing maneuver, and the following vehicle on the target lane accepts a reduced minimum safety distance between the lead and following vehicles. A value of 0.6 for the safety distance reduction factor 0.6 means that the vehicle on the target lane accepts an additional 40% reduction in the safety distance. Ahmed et al. [56] suggested a value of one for HCVs in a platoon, i.e., they suggested that HCV platoons must use extremely cautious behavior and maintain the minimum safe distance when changing lanes.

The micro-simulation model also considers “lane changing distance”. This input parameter refers to the point from which a vehicle will start to change lanes. As the study area’s acceleration lane length was about 350 m, we modified the lane changing distance to 350 m instead of PTV’s [52] recommended value of 200 m [51].

We used SSAM to conduct the safety performance evaluation [63]. This approach identifies potential conflicts between two vehicles. A conflict is defined as an interaction between two vehicles that has the potential for a collision. On the basis of SSAM, conflicts are categorized as crossing conflicts, rear-end conflicts, and lane-changing conflicts. The evaluation identifies conflicts that have a high correlation with cash frequency and estimates time-to-collision (TTC) and post-encroachment time (PET). TTC is defined as the time before a collision between two vehicles to collide if they do not change direction, speed, or acceleration. PET is the time difference between the time at which a first vehicle left a location and the time at which a second vehicle arrived at the same location [64,65]. We used a TTC of 1.5 s and a PET of 5 s as suggested by Gettman et al. [41].

#### 4.1.2. Calibration of Micro-Simulation Model

Following the Wisconsin Department of Transportation's (WisDOT) guidelines, we simulated the Base Model 30 times to replicate existing roadway conditions at the 95% confidence level [47,66,67]. We then applied the Geoffrey E. Havers (GEH) statistical test and the Welch two-sample *t*-test [68]. We used hourly traffic volume on the freeway and merging ramp as the measure of performance for GEH [47,69]. The GEH value was less than 5 (see Table 4), indicating that the Base Model simulation of hourly traffic volume is similar to the observed traffic volume.

**Table 4.** GEH Base Model test results.

Roadway Type	Field Observed Traffic Volume (vph)	Simulated Base Model Traffic Volume (vph)	GEH Value
Freeway	6100	6033	0.86
Ramp	1100	1058	1.28

We used the Welch *t*-test to validate the speed accuracy [68]. Our null hypothesis was that the simulation and field observations of the average speed on the freeway's five lanes were equal. Table 5 summarises the results and shows that the average speed for each freeway lane was not significant at the 95% confidence level (*p*-value > 0.05). As the null hypothesis cannot be rejected, we considered the Base Model simulation of freeway travel speeds to be acceptably close to the observed speed observations.

**Table 5.** Two-sample *t*-test Base Model results.

Freeway Lanes	Average Speed (Simulation Result) (Km/h)	Standard Deviation (Km/h)	Two Sample		
			Degrees of Freedom (df)	<i>t</i> -Statistic	<i>p</i> -Value
Lane 1	105.69	5.15	6093.10	−1.56	0.12
Lane 2	97.75	6.38	6095.30	0.87	0.38
Lane 3	95.62	7.63	6094.40	−1.03	0.31
Lane 4	92.98	8.55	6094.70	−0.91	0.36
Lane 5	91.69	8.55	6093.60	−0.44	0.66

We also compared speeds on the ramp with the speeds simulated by the Base Model. According to the HERE [44] database, vehicles required on average 66 s to travel from the start of the ramp to the gore point. In the Base Model, passenger vehicles and HCVs travelled the ramp within 66 s (standard deviation ± 8.04 s). The Welch *t*-test was used again to compare the HERE database with the Base Model. As the results were not statistically significant at the 95% confidence level (df = 1057; *t*-statistic = 0.29; *p*-value = 0.77), the Base Model travel times reasonably simulated the HERE database on the ramp.

#### 4.1.3. Development of Test Scenarios

The Base Model (BM) represented the do-nothing scenario and was developed with 350 m acceleration lane length, as mentioned in Section 2. However, the estimated acceleration lane length using the proposed analytical model (discussed in Section 3) suggests a minimum 600 m acceleration lane length for two HCV platooning operations, regardless of different time headways (0.6 s and 1.2 s). Therefore, eight test scenarios (alternative models) were considered to investigate the operational impact of Level 4 HCV platooning on combinations of different acceleration lane lengths (existing 350 m and extended to 600 m), different time headways (0.6 s and 1.2 s), and different market penetration rates (0%, 5%, and 10%). The extended acceleration lane length was designed to provide extra time that would allow platooned HCVs to merge on the freeway together without facing delay.

The study developed a total of eight Alternative Models in VISSIM as comparisons with the Base Model. Table 6 shows the configuration for considered Alternative Models.

**Table 6.** Alternative model parameters.

Alternative Models	Headway (s)	Market Penetration Rates (%)	Acceleration Lane Length (m)
AM1	0.6	5	350
AM2	1.2		
AM3	0.6	10	
AM4	1.2		
AM5	0.6	5	600
AM6	1.2		
AM7	0.6	10	
AM8	1.2		

## 5. Results of Micro-Simulation Modeling

This section presents the results of the micro-simulation modelling. We performed a total of 270 simulations (9 models  $\times$  30 runs) to examine the operational and safety impact of HCV platooning on the study area's freeway merging segment. We used the travel time each vehicle required to merge onto the freeway from the start of the ramp and the number of conflicts as the measures of effectiveness (MOE) [70].

### 5.1. Travel Time to Merge

Two approaches, namely, box plots and statistical testing, were used to analyse the impact of HCV platooning on all vehicles (i.e., passenger vehicles as well as HCVs) and only HCVs. As shown in Figure 2, both box plots show the time required to merge onto the freeway by all vehicles. Box plot (a) was for all vehicles and box plot (b) was for HCVs, including conventional HCVs in the Base Model and platooned HCVs in the alternative models. Each box plot shows the results for five statistics related to the travel time to merge: (1) minimum travel time to merge, (2) 15th percentile travel time to merge, (3) average travel time to merge, (4) 85th percentile travel time to merge, and (5) maximum travel time to merge.

Vehicles seek to merge onto the freeway from the acceleration lane immediately, but if there is no acceptable gap, vehicles need to travel on the acceleration lane or may need to wait at the end of acceleration lane to look for an adequate gap for merging. This gap searching and waiting time causes an increase in the merging time or delays. Similar to the real-world merging circumstance, as shown in Figure 2, the lowest travel time to merge result indicates that vehicles merged immediately without needing additional time to merge because merging vehicles encountered fewer vehicles on the freeway's right-most lane. The maximum travel time to merge result, however, demonstrated a delay or increase in travel time since merging vehicles had to wait on the merging lane until they found a safe, adequate gap due to traffic on the freeway's rightmost lane. The above discussion illustrates that the outcomes are consistent with actual merging circumstances.

The *t*-test and Kolmogorov–Smirnov (KS) test are widely used to compare data from two samples. The *t*-test compares the values of the means, but our estimated results did not follow a normal distribution and are unsuitable in this instance. The KS test is an alternative that compares the cumulative distribution of the two samples [71–73].

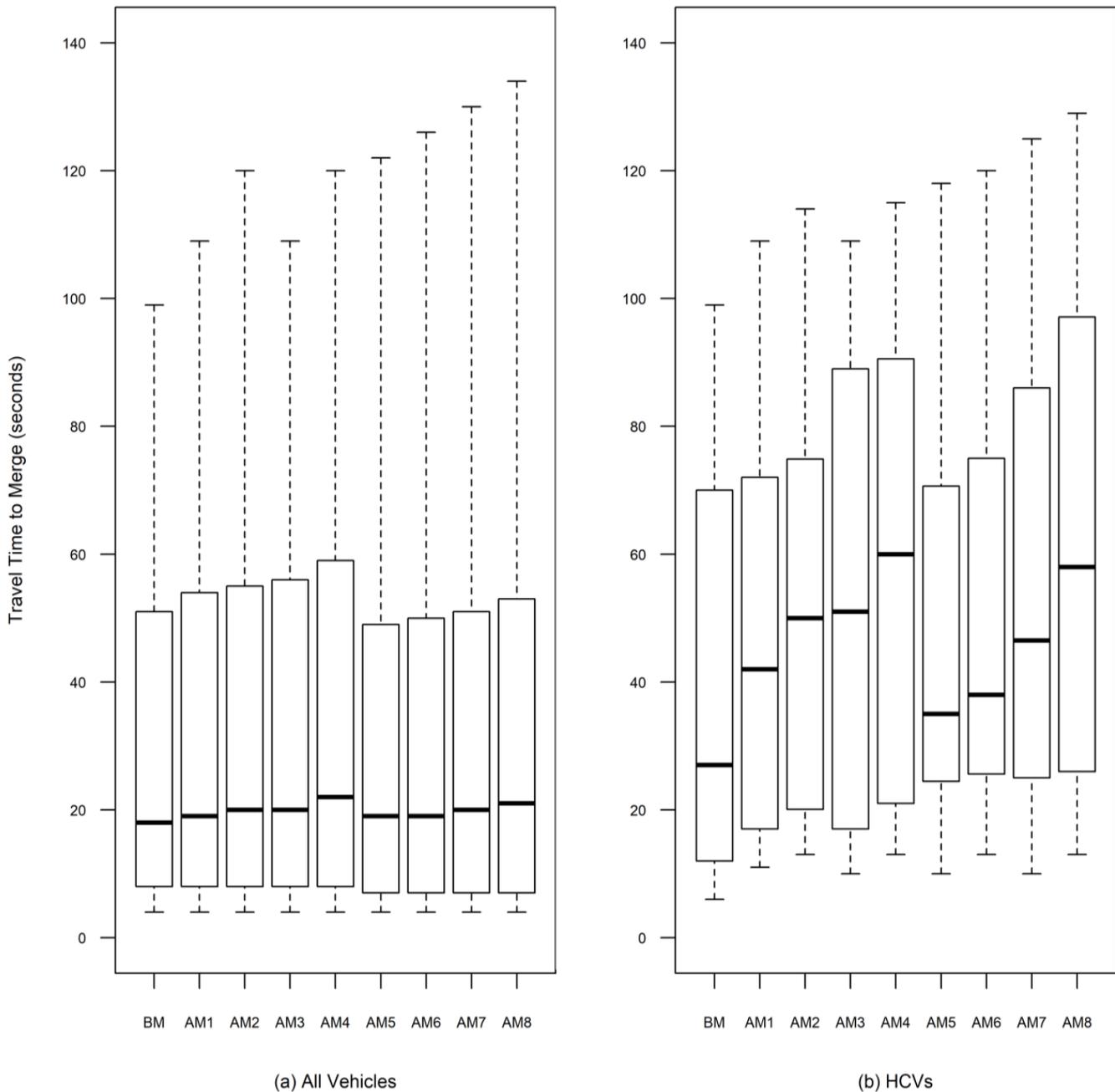
KS tests were applied to the information shown in Figure 2 to investigate whether the time to merge cumulative distributions obtained from a comparison of the BM were similar to the time to merge cumulative distributions obtained from alternative models. The KS test's D-statistic provided a statistical basis for comparing the travel times required to merge. The null hypothesis was that the travel time required to merge in each alternative model was equal to the travel time required to merge in the Base Model. We calculated the D-statistic using Equation (19):

$$D = \max|F_{n1}(X) - F_{n2}(X)| \quad (19)$$

where

$F_{n1}(X)$  = cumulative frequency distribution of BM; and

$F_{n2}(X)$  = cumulative frequency distribution of Alternative Model.



**Figure 2.** Model comparison for estimated travel time to merge.

Table 7 summarizes the results of the travel times to merge analyses for all vehicles and for HCVs for all the models. The table shows the 15th percentile, average, and 85th percentile time to merge speeds; the KS test D-statistic; the  $p$ -value; and the significance level of the comparisons with the BM. Most comparisons were significant at the 99% confidence level.

We made the following observations from Figure 2 and Table 7 for all vehicles:

The finding of this study suggests that the operation of HCV platooning increased the average merging time. For all vehicles, the average travel times to merge for 0%, 5%, and 10% HCV platooning were slightly lower for the 0.6 s compared to 1.2 s headways. The

average merging time for the operation of 5% HCV platooning with 0.6 s headways was lower than 5% HCV platooning with 1.2 s headways, and the average travel time to merge for 5% HCV platooning with 0.6 s headways was also higher than the 0% HCV platooning operation. These results indicate that the number of HCVs in a platoon, as well as the physical gap between platooned HCVs, are contributing factors to a longer merging time.

**Table 7.** KS test results for travel time to merge.

Vehicle Category	VISSIM Model	15th Percentile	Average	85th Percentile	KS Test D-Statistic	p-Value	Significance Level *
All	BM	8	18	51	NA <sup>1</sup>	NA <sup>1</sup>	
	AM1	8	19	54	0.021	0.2	
	AM2	8	20	55	0.042	$2.20 \times 10^{-16}$	***
	AM3	8	20	56	0.039	$2.20 \times 10^{-16}$	***
	AM4	8	22	59	0.063	$2.20 \times 10^{-16}$	***
	AM5	7	19	49	0.141	$2.20 \times 10^{-16}$	***
	AM6	7	19	50	0.135	$2.20 \times 10^{-16}$	***
	AM7	7	20	51	0.065	$2.20 \times 10^{-16}$	***
	AM8	7	21	53	0.062	$2.20 \times 10^{-16}$	***
HCVs	BM	12	27	70	NA <sup>1</sup>	NA <sup>1</sup>	
	AM1	17	42	72	0.034	0.14	
	AM2	20	50	75	0.277	0.002	**
	AM3	17	51	89	0.252	$7.32 \times 10^{-7}$	***
	AM4	21	60	91	0.327	$2.42 \times 10^{-11}$	***
	AM5	24	35	71	0.387	$4.77 \times 10^{-6}$	***
	AM6	26	38	75	0.371	$1.01 \times 10^{-5}$	***
	AM7	25	46	86	0.428	$2.22 \times 10^{-16}$	***
	AM8	26	58	97	0.414	$1.22 \times 10^{-15}$	***

<sup>1</sup> Note: NA indicates a value is not applicable. \* Significance level: <0.01 "\*\*\*\*"; <0.05 "\*\*\*"; >0.1 " " .

For all vehicles and the existing acceleration lane length (350 m), the box plot in Figure 2a and Table 7 show that the BM's 85th percentile travel time to merge was 51 s per vehicle. AM1 (5% HCV platooning, 0.6 s headway) increased travel time to merge by 3 s (i.e., to 54 s) per vehicle. The 85th percentile travel times to merge increased for AM2 (5% HCV platooning, 1.2 s headway), AM3 (10% HCV platooning, 0.6 s headway), and AM4 (10% HCV platooning, 1.2 s headway). AM4 shows the largest increase (8 s) compared to BM. This result suggests that market penetration rate is another contributing factor in addition to the physical gap between platooned HCVs and the number of HCVs in a platoon. The increase in the number of platooned HCVs on the freeway merging ramp will lead to more delay.

The KS test for all vehicles found that the distribution of travel times in AM1 was not statistically significant, i.e., operational conditions under HCV platooning with existing acceleration lane length, 5% HCV platooning, and 0.6 s headway are likely to be comparable to existing operational conditions. In the case of AM2, AM3, and AM4, the distributions of travel times were statistically significant at the 99.9% confidence level, i.e., a small percentage of HCV platooning with the existing 350 m of acceleration lane created significant delays on the study corridor merging ramp.

For all vehicles and the extended acceleration lane length (600 m), the boxplots in Figure 2a and Table 7 show that AM5 (5% HCV platooning, 0.6 s headway) reduced the 85th percentile travel time to merge by 2 s per vehicle in comparison to the BM and 5 s per vehicle in comparison to AM1. The finding suggests that the extended acceleration lane allows all vehicles in AM5 to find a suitable gap and merge faster without experiencing delay when compared to all vehicles using AM1's acceleration lane length (350 m).

AM6 (5% HCV platooning, 1.2 s headway) reduced travel time to merge for all vehicles by 1 s per vehicle in comparison to the BM, 4 s per vehicle in comparison to AM1, and 5 s per vehicle in comparison to AM2. The AM6's travel time to merge result indicates that

the extended acceleration lane length, like AM5, is beneficial for improving merging time. In contrast, AM6 merge travel time was longer for all vehicles in comparison with AM5. The comparison of AM5 and AM6 merging times for all vehicles suggests an increase in merging time for extending the physical distance between platooned HCVs.

For AM7 (10% HCV platooning, 0.6 s headway), the 85th percentile travel time was the same as for the BM, and for AM8 (10% HCV platooning, 1.2 s headway), the 85th percentile travel time increased by 2 s. However, compared to AM3 and AM4, for AM7 and AM8, all vehicle travel time was reduced. This outcome indicates the advantage of reducing merging time for the extended acceleration lane length. However, the comparison of both AM7 and AM8 (10% HCV platooning) with AM5 and AM6 (5% HCV platooning) models also suggests that the increase in market penetration HCVs of platooning cause the reduction in travel time saving benefit, even with the extended acceleration lane length.

The KS test results for all vehicles showed that the distribution of travel times to merge for all vehicles for AM5, AM6, AM7, and AM8 were statistically significant at the 99.9% confidence level. This result illustrates that the extended (600 m) acceleration lane improved merging time significantly on the study corridor merging ramp; however, the increase in platooned HCVs reduced the merging time saving benefit.

We made the following observations from Figure 2 and Table 7 for HCVs:

Figure 2b and Table 7 show that the travel time to merge pattern for HCVs was similar to the patterns for all vehicles for eight alternative models. The result demonstrates that HCVP\_1.2H requires more time to merge compared to HCVP\_0.6H. On the other hand, the increase in platooned HCVs increased the overall merging time for HCVs.

Compared to the BM for HCVs, AM1 (5% HCV platooning, 0.6 s headway) 85th percentile travel time to merge increased by 2 s per HCV in the platoon; for 5% HCVP\_1.2H, operation travel time to merge for AM2 increased by 5 s; for AM3 (10% HCVP\_0.6H), it increased by 19 s; and for AM4 85th percentile travel time to merge, it increased by 21 s per platoon of HCVs. We noticed that the magnitude of increased in 85th percentile merging time for HCVs was higher than all vehicles merging time. This result implies that platooned HCVs are responsible for an increase in merging time.

From Figure 2b, we also observe that to travel on an existing acceleration lane (350 m), 5% HCVP\_0.6H (AM1) required 1.6 times (average 42 s) more merging time in comparison to BM, while both AM2 (average 50 s) and AM3 (average 51 s) required 1.9 times more merging time than BM (average 27 s). Similarly, 10% HCVP\_1.2H (AM4) needed 2.2 times (average 60 s) more merging time than BM's conventional HCVs.

The 600 m of acceleration lane enabled a reduction in the average merging time compared to AM1, AM2, AM3, and AM4, although the average merging time in comparison to BM was 1.3 times higher for AM5, 1.4 times higher for AM6, 1.7 times higher for AM7, and 2.2 times higher for AM8.

From AM5 travel time to the merge result for HCVs, we observed that the extension of the acceleration lane allowed HCVP\_0.6H to merge in 71 s, which was only 1 s more than BM's HCV travel time to merge and 1 s less than AM1's HCV travel time to merge. Similar to AM5, the AM6 model indicated that HCVP\_1.2H required 75 s travel time to merge, which indicated no changes in merging time compared to AM2's HCV travel time to merge.

For AM7 and AM8, however, even with the extension of the acceleration lane, HCVs' merging time increased rather than decreased. The increase was 16 s for AM7 compared to BM's HCV merging time, and for AM8, 27 s compared to BM's HCV merging time. The increase in merging time by 27 s in AM8 explained that HCVP\_1.2H can travel approximately 750 m less distance at 100 km/h than conventional HCVs, even if both conventional HCVs and platooned HCVs started their journey at the same time.

The extension of the acceleration lane allowed platooned HCVs to travel on the acceleration lane more in order to find out the required gap for merging instead of waiting and developing spillback on the merging ramp, resulting in an increase in the merging

time. During this situation, other vehicles such as passenger vehicles and conventional HCVs can merge whenever they find an adequate merging gap.

The KS test result indicated that HCV merging time for the alternative model AM1 was not statistically significant at the 90% confidence level when compared with the base model BM. This implies that the existing acceleration lane length of 350 m was sufficient for the 5% HCVP\_0.6H scenario without deteriorating roadway operational performance.

The overall findings of this study suggest that the operation of HCV platooning regardless of different headways will cause negative for merging through the existing 350 m acceleration lane. The recommended 600 m acceleration lane length based on the estimation of our proposed analytical model, however, will be beneficial to keep maintaining the overall same operational performance as the BM (existing) condition. Nevertheless, compared to all vehicles, HCVs will encounter a more acute operational condition for the HCV platooning operation. On the other hand, the physical gap between platooned HCVs had a significant effect on the freeway merging ramp operation. HCV platooning with 1.2 s headways require more time to merge on the freeway from the ramp compared to HCV platooning with 0.6 s headways. Furthermore, an HCV platooning penetration rate of 10% may create significant delays compared to 0% and 5% HCV platooning, not only for HCVs but also for all vehicles. A higher penetration rate will likely further increase the delays, even with the extended 600 m acceleration lane length. Extending the length of the acceleration lane will improve operational performance by reducing the 85th percentile merging time 3.9% for the operation of 5% HCV platooning with 0.6 s headways.

### 5.2. Number of Conflicts

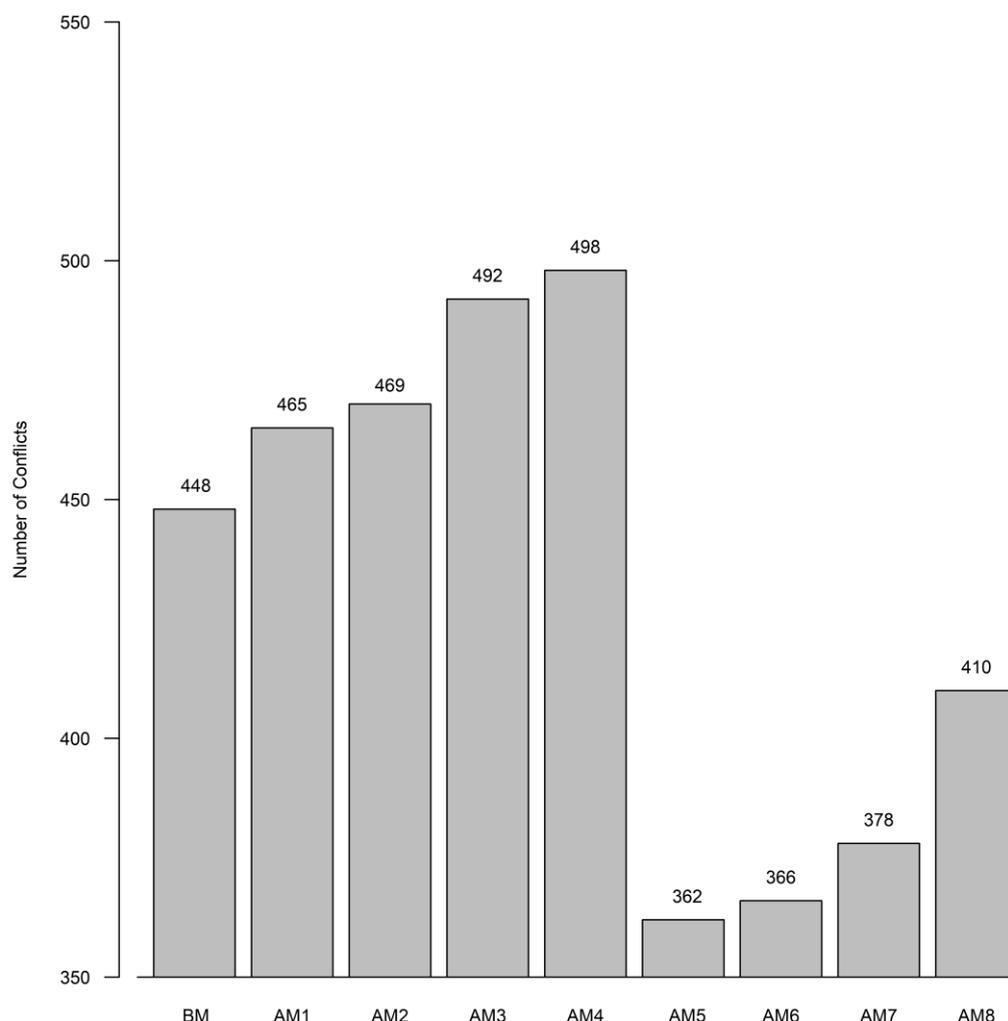
To understand the risk associated with HCV platooning, we performed a surrogate safety assessment in which the total number of conflicts was estimated for all nine models. As mentioned earlier, conflicts can be categorized as crossing conflicts, rear-end conflicts, and lane-changing conflicts. All three conflict types were aggregated together for this analysis.

We used the SSAM approach [41,70] to estimate the number of potential conflicts. Figure 3 shows the estimated number of conflicts for each model.

Figure 3 shows that

- Compared to the BM, the models for the existing acceleration lane length of 350 m (AM1, AM2, AM3, and AM4) had a higher number of conflicts. This result implies that an acceleration lane length of 350 m in this context leads to serious safety concerns on the merging ramp segment, regardless of HCV platooning penetration rate or headway. Compared to the BM value of 448 conflicts, the models for the extended acceleration lane length of 600 m had reduced conflicts of 362, 366, 378, and 410 for AM5, AM6, AM7, and AM8, respectively.
- Within the models for an acceleration lane length of 350 m, the number of conflicts was higher for the 1.2 s headway models than for the 0.6 s headway models, and the number of conflicts was higher for the 10% market penetration models than for the 5% market penetration models. The same relationship was observed for the extended acceleration lane length of 600 m.

The result suggests that the 600 m acceleration lane length for HCV platooning regardless of different headway (0.6 s and 1.2 s headway) on the basis of proposed analytical model provides substantial conflict reduction benefit. The extension of acceleration lane length to 600 m will improve safety by reducing the number of conflicts to 19.2% for the 5% HCV platooning operation (0.6 s headway). The safety concerns increase with a greater percentage of HCV platooning and a larger distance between platooned vehicles.



**Figure 3.** Estimated number of conflicts for each model.

## 6. Conclusions and Recommendations

V2V technology appears to offer promising potential for future goods movement. Level 4 HCV platooning requires the lead vehicle to have a human driver, but one or more closely following HCVs may be driverless. The primary objective of this study was to evaluate how the introduction of HCV platooning on freeway merging segment in North America may influence highway safety and operational performance under mixed traffic conditions on the basis of the analytical and simulation methods, notably in terms of the acceleration lane length parameter utilized in existing geometric design standards.

### 6.1. Summary of Results

The analytical approach used a newly proposed model in this study to estimate the required acceleration length for two HCV options (two WB-20 HCV platoons travelling with a shorter and longer headway between the HCVs). As expected, our proposed model for an HCV platoon anticipated longer acceleration lane lengths than those recommended by 2018 AASHTO and 2017 TAC. Both 2018 AASHTO and 2017 TAC acceleration lane lengths are insufficient for HCV platoons' operation. The analytical model findings suggest the minimum acceleration lane length is about 600 m for the operation of platooned HCVs, regardless of different headways (0.6 s and 1.2 s headway) for the selected freeway and merging ramp instead of at least a 360 m acceleration lane length recommended by 2018 AASHTO [3] and 350 m recommended by 2017 TAC [2]. The insufficient acceleration lane length may cause a significant safety concern and considerable delays for merging traffic, especially for HCV platooning.

The simulation approach used a micro-simulation tool to analyze the impact of HCV platooning. We first tested Level 4 HCV platooning impact at low penetration rate and two different time headways following existing geometric design guidelines using a VISSIM micro-simulation model. We evaluated the effect on operational performance of HCV platooning by measuring the required travel time for merging. The BM's average travel time to merge has been compared to the average travel time of eight other alternative models. The simulation analysis revealed that the HCV platooning merging time was significantly longer than the average merging time for all vehicles. In addition, the average merging time of HCV platooning through a 350 m acceleration lane was longer than that of a 600 m acceleration lane. The result indicates an improvement in average merging time for the extension of the acceleration lane. The average merging time of 5% HCV platooning through a 600 m acceleration lane regardless of 0.6 s or 1.2 s headway was significantly lower than the average merging time through a 350 m long acceleration lane of 5% HCV platooning for both 0.6 s and 1.2 s headway. A similar trend was observed for the average merging time of 10% HCV platooning.

The simulation result showed that the average travel time for merging was increased for both 5% and 10% HCV platooning operations when compared to the 0% HCV platooning operation. On the other hand, for the same market penetration, platoons with a 1.2 s headway needed more merging time than a 0.6 s headway.

We also analyzed the safety impact on the total number of conflicts for each scenario. A higher number of conflicts was observed for both 5% and 10% HCV platooning, regardless of 0.6 s and 1.2 s headway for merging through a 350 m long acceleration lane when compared to the base scenario. The safety analysis results suggested significant improvement in terms of reducing the number of conflicts for both 5% and 10% HCV platooning if the acceleration lane was extended to 600 m. The increased distance will need to be considered as a trade-off with increased construction cost and available space but may be worthwhile on facilities with substantial goods movement and HCV platoons.

## 6.2. Limitations and Future Research

There are some limitations with this study that can be addressed in future research. Future V2V technology and traffic conditions are still uncertain. Existing V2V technology allows a passenger vehicle to cut in and out safely between platooning HCVs [74,75], but this study did not consider such maneuvers. Furthermore, on the basis of the recent progression of V2V communication range, the National Highway Traffic Safety Administration (NHTSA) affirms that vehicles equipped with V2V technology will be capable of communicating with one another at a distance of approximately 300 metres [57]. If future V2V technology allows for long range communication and permits cut-in and cut-out between platooned vehicles, the requirement of acceleration lane length estimated in this study may be less. Furthermore, yielding of the freeway right-most lane traffic while HCV platooning is merging on the freeway from ramp proper would alleviate potential safety concerns for HCV platooning and other vehicles [24].

Due to a lack of HCV platoon operations in the real-world traffic, no study has yet calculated typical headway values for HCV platoons with other vehicles (i.e., the headway between a platoon and a vehicle ahead or behind). Field observations do not indicate the headway between a passenger vehicle and an HCV platoon. This study considers minimum 1.5 s headway between a passenger vehicle and an HCV platoon, since Houchin et al. [76] observed 1.5 s headway between a passenger vehicle and an HCV on the basis of the field observation. Future work must consider different platoon headways for HCVs, especially in a V2V environment where many vehicles can communicate. In this case, minimum headways could differ from those assumed in the study. It will take time to collect enough data, as HCV platooning operation from ramp roadways to freeway is not yet common in North America; however, testing of the HCV platooning operation is ongoing in many areas of the world. Furthermore, this research did not consider vertical slope's effect on estimating acceleration lane length. Steep slopes reduce the speed of an

HCV platoon and the merging vehicle's acceleration, which may impact on the acceleration lane length estimation.

As mentioned, AASHTO (2018) suggests a minimum 360 m long acceleration lane length [3]; however, it also recommends different acceleration lane length for different speeds of the freeway and merging on-ramp. Similarly, our proposed model also asserts acceleration lane length for different freeway and merging ramps' design speed. Several estimated acceleration lane lengths for HCV platooning considering slow-speed freeways and merging ramps fell within AASHTO's (2018) recommended value [3]. However, from the simulation analysis, we observed a negative impact from the HCV platooning operation, regardless of different headways and market penetration rate along the selected corridor's 360 m long acceleration lane. On the other hand, the 600 m acceleration lane length showed significant improvement in terms of safety and operation. Several North American jurisdictions already allow LCV operations on freeway corridors during specific times of the day. Analytical and simulation analyses indicated that the freeway merging segment designated for LCV operation with minimum 600 m acceleration lane length could be used for HCV platooning. Nevertheless, HCV platooning will encounter less traffic when merging on the freeway where traffic volume is low on the freeway and the merging ramp. The recommended level of service should be investigated in a future study at which 5% HCV platooning (0.6 s headway) could be operated without interruptions. As a result, we propose that during certain hours of the day, freeway and merging ramp with low traffic volume could be permitted to allow 5% of platooned HCVs (0.6 s headway) to operate like LCV operations.

The findings in this study will help transportation engineers as well as planners understand the implications of HCV platoons and determine appropriate locations to permit HCV platooning on freeways.

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## Appendix A

**Table A1.** *t*-test results for acceleration lane length.

Vehicle Classification	Models	Existing Acceleration Lane Length (m)	Estimated Acceleration Lane Length (m)	<i>t</i> -Test	<i>p</i> -Value
Passenger vehicle	CAMMSE (Qi et al., 2019) [12]	183	175	1.59	0.11
	2018 AASHTO [3]	184	175	1.41	0.15

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