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Characterization of heavy vehicle headways in oversaturated interrupted conditions: Towards development of passenger car equivalency factors

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ABSTRACT

Passenger car equivalency (*PCE*) of heavy trucks is often studied using filed observation and microscopic simulation models, especially for signalized intersections. While the Highway Capacity Manual recommends a single value regardless of the percentage of those heavy vehicles, literatures have shown that this equivalency is affected by different factors, including the trucks percentage. This research aims to examine the *PCE* under different level of traffic and heavy trucks demands. First, field measurements were collected and used to examine the characteristics of heavy vehicle and passenger car headways in over-saturated interrupted flow conditions. Field observations were then used to calibrate a microscopic simulation model. The model was then used to evaluate impact on headways of different levels of congestion and heavy vehicle percentages. Field results show that truck headways are about 2.3 those of passenger cars. The results also show that trucks are 1.5 more likely to be first in a queue when compared to passenger cars and 1.7 times more likely to be in first four vehicles in a standing queue. Passenger cars immediately behind trucks had longer than average headway. The simulation results suggest that *PCE* increases nonlinearly with increase in congestion level and with percentage of trucks; *PCE's* increase becomes less marked once sever congestion (stop-and-go with increasing queue lengths) conditions set in.

Introduction

The concept of headways is important to study traffic flow characteristics. Time headways and space headways are directly linked to the fundamental measures that are used to describe traffic flow. Easily measured time headways can be used to determine the capacity or saturation flows. Headways can be used to extend green times at a vehicle-actuated traffic signal, measured by actuators. Headways can also be used at unsignalized intersections to study the attributes of gap acceptance and capacity of stop-controlled intersections. However, headways are often affected by dynamic characteristics of the different vehicles. Therefore, it is important to differentiate and understand the headways characteristics for different vehicles.

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The difference between car and truck headways is critical in areas where there is a significant presence of both types of vehicles, especially when high percentage of truck traffic is observed. This assumes further importance in congested interrupted conditions where timing of clearance intervals and green extensions become more consequential. Since trucks accelerate from a stop at a slower rate than cars, and since trucks are longer than cars, they will have longer headways. This effect can be more pronounced in interrupted conditions when traffic flow is at saturation.

This study uses empirical data and microscopic simulation to examines headway relationships to different levels of congestion and vehicle mix using field measured time headways at a signalized intersection during oversaturated conditions. Simulation modeling has been widely used in traffic engineering analysis (Ferwati et al., 2018; Dion and Ghanim, 2007), including saturation flow and headway analysis (Amini et al., 2019). Time headways are used since they can be easily measured using a stopwatch, video image processing or other traffic-measuring device (Ghanim and Shaaban, 2018b, Ghanim, 2011; Ghanim and Abu-Lebdeh, 2018). A signalized intersection is used since it is the location where vehicles will repeatedly be accelerating from a stop position, and where frequent stop-and-go pattern can also be observed. Thus, capturing those patterns can be recorded to evaluate their impact on headway. Interruption in this study refers to either: (1) stopping of vehicles at the subject approach due to signal action, or (2) stopping of vehicles due to growing downstream queue. For this study, oversaturated conditions will be used to ensure that vehicles will be in car-following mode. Oversaturation here refers to conditions where traffic queues persist and grow with time. The term "heavy vehicle" and "truck" in this study refers to heavy trucks. Light single unit trucks are not included.

Typically, the value of the passenger car equivalency (*PCE*) depends on several factors, including the level of congestion and traffic mixture. The percentage of trucks in the traffic stream is neither monotonic nor linear. The assumption that the *PCE* value is insensitive to the level of trucks presence in both undersaturated and saturated conditions is intuitive. It is expected that as the level of congestion goes up, the presence of trucks become more pronounced, disturbing, and impeding to the traffic stream when compared to absence of trucks. Therefore, it is expected that the *PCE* value would increase.

The objective of this research is to study the variation of heavy vehicle headways with different levels of congestion, traffic demand, and vehicle mix as a prelude to determining how truck passenger car equivalency (*PCE*) factors may vary and quantify this variation. Since passenger car equivalency factors have significant impact on capacity and level of service analyses at signalized intersections, an implicit objective is to examine if and how much of a need there is to adopt variable *PCE*.

Background

Several studies used headways to examine the topic of heavy vehicle operational characteristics and their passenger car equivalencies. Many of these studies, however, dealt with unsaturated conditions. Greenshields et al. proposed a Passenger Car Equivalent of 2.63 for a vehicle in non-leading position and 4.05 for a vehicle in leading position (Greenshields et al., 1947). These values were calculated based on the analysis of headways. The Passenger Car Equivalent was defined as a ratio of the average headways for the vehicles of interest to the average headways for passenger cars, as shown in Equation (1).

$$PCE_u = \frac{h_u}{h_c} \tag{1}$$

where:

PCE_u: Passenger Car Equivalent for vehicles of class u
h_u: Average headway of vehicles of class u
h_c: Average Headway of Passenger Cars

Molina (Molina Jr, 1987) considered the increase in headway for the vehicles queued behind the heavy vehicle. The Passenger Car Equivalent was calculated with the relationship shown in Equation (2). It was found from this study that the position of single unit trucks in the queue had no significant effect whereas, for semi-trailers, the position of the vehicle had a pronounced influence on the resultant *PCE* values. A *PCE* of 1.7 was recommended for light trucks and 3.7 for heavy ones.

$$PCE_t = \frac{h_t + \Delta h}{\bar{h}_c} \tag{2}$$

where:

PCE_t: Passenger Car Equivalent for Heavy Vehicles (i.e., Trucks)
h_t: Average headway of Heavy Vehicles (i.e., Trucks)
$\bar{h}_c$: Saturation flow Headway of Passenger Cars
Δh: Headway Increase for Passenger Car following Trucks

The highway capacity manual employs a heavy vehicle adjustment factor (f_{HV}) to account for the heavy vehicles at intersections (Transportation Research Board, 1965; Transportation Research Board, 1985; Transportation Research Board, 1994;

Transportation Research Board, 1997; Transportation Research Board, 2000; Transportation Research Board, 2010). Equation (3) is used to compute the value of f_{HV}.

$$f_{HV} = \frac{1}{1 + P_t(PCE_t - 1)} \tag{3}$$

where:

PCE_t: Passenger Car Equivalent for heavy vehicles
P_t: Percentage of heavy vehicles (trucks)
f_{HV}: Heavy vehicle adjustment factor for traffic flow

For intersections, the 1985 HCM recommended a Passenger Car Equivalent of 1.5. A value of 2.0 was given by the 1994 and 1997 HCM. This value was set to 1.5 in 2000 HCM. The recommended value in the latest HCM 2010 is back to 2.0. For each of those HCM editions, the *PCE* value is constant irrespective of the kind of trucks, trucks percentage or the volume of traffic (Transportation Research Board, 1965; Transportation Research Board, 1985; Transportation Research Board, 1994; Transportation Research Board, 1997; Transportation Research Board, 2000; Transportation Research Board, 2010). It should be noted that HCM 2016 has combined the adjustment of heavy vehicles and grades into one adjustment factor in the form of an equation with two independent variables, regardless of the congestion level (Transportation Research Board, 2016). Based on this equation, the *PCE* ranges between 1.0 and 2.31.

Keller et al. used TRANSYT-7F to study a macroscopic setting of an urban network, to develop Passenger Car Equivalent as a function of vehicle size, signal timing and traffic volume (Keller and Saklas, 1984). The ratio of total travel time of heavy vehicles to passenger cars was taken for developing such a Passenger Car Equivalent. A Passenger Car Equivalent value of 1.09 for a single unit truck and 1.53 for a semi-trailer were recommended.

Saha et al. collected data from ten different signalized intersections to (Transportation Research Board, 2016) calculate the *PCE* for different vehicle types using the headway ratio method (Partha et al., 2009). Their study found in general that the observed *PCEs* are less than those used in Geometric Design Highway in Bangladesh. The largest vehicles in this study were classified as buses, with a *PCE* value of 2.16.

Rahman et al proposed a new method to estimate *PCE* based on the additional delay induced by large vehicles (Rahman et al., 2003). Data were collected from seven signalized intersections with 15 approaches that are located in Yokohama city of Kanagawa prefecture of Japan. It was reported in this study that a *PCE* value of 1.183 is associated with an observed percentage of 10% in the queues. This *PCE* value continuously increases as the percentage of large increases, to reach 1.564 when the queue consists of 90% of large vehicles.

NETSIM was used by Sumner et al. for developing the Passenger Car Equivalent value for an urban arterial within two signalized intersection (Sumner et al., 1984). The *PCE* value for single unit trucks was 1.10 to 1.18 for level of service *D* and *B*. *PCE* values for semi-trailers were found to be 1.45 and 1.53 for level of service *D* and *B*.

Sharma and Biswas (2020) reviewed and summarized 63 scientific research papers (out of 587 manuscript) that are detailing the Passenger Car Unit (PCU). In their literature review, they evaluated the values of PCU under different traffic demand conditions, geometric configurations and other factors. The paper also discussed the PCU development approaches and methodologies. They concluded that the PCU can be affected by the region, since driving behavior and cultures are different from one region to another. They also found that very few studies have adopted a single PCU value for different vehicle classes, and that most of the studies, has found that PCU tends to change in response to the changes in traffic demand or geometric configurations.

Several other studies have examined and evaluated the passenger car equivalency factor (*PCE*) (Al-Kaisy et al., 2005; Ye and Zhang, 2009; Radhakrishnan and Mathew, 2011; Shalini and Kumar, 2014; Skabardonis et al., 2014; Obiri-Yeboah et al., 2014; Badhrudeen et al., 2016; Mohan and Chandra, 2017). For some of these studies, the Passenger Car Equivalent values were expressed as values, which varied with some of the input parameters, while others recommended a constant value. This study uses measured headways in oversaturated conditions interrupted conditions to further understand the relative impact of heavy vehicles is such conditions, and to propose a *PCE* factor.

Experimental setup

A site with significant large trucks traffic was selected. Traffic at one approach was monitored and data were collected using a video camera with timestamp and it was supplemented with a stopwatch and audio recording. The methodology for measuring saturation flow rate in the Highway Capacity Manual 2010 was used here to guide the fieldwork (Transportation Research Board, 2000; Transportation Research Board, 2010). Once traffic headways were collected and processed, they were classified into four different groups, Car following Car (*CFC*), Car following Truck (*CFT*), Truck following Car (*TFC*) and Truck Following Truck (*TFT*). Furthermore, headways for the cars and trucks were also estimated. The traffic network was modeled within microscopic simulation environment, namely VISSIM (PTV Planung, 2017). These headways, traffic counts and signal timings were then used to calibrate the network modeled in VISSIM using 10 multiple runs with different random seeds. The calibrated network was then used to evaluate headways with different traffic demand and signal timing patterns.

Site selection and characteristics

For the purpose of this study, the two key elements were the significant presence of trucks and the persistence of saturated conditions. Since factors other than proportion of heavy vehicles can affect vehicle headways, the process of selecting a suitable location included attempting to select a location with conditions that were as close to ''ideal conditions" as possible. This way, effects of lane width, turning movements, grades, on-street parking, and bus blockage are eliminated.

Several locations were initially evaluated in Lexington, Kentucky. The intersection that was ultimately selected for this study is the intersection of Newtown Pike (KY 922) and Citation Boulevard. This intersection is about one and a half kilometer south of the junction of Newtown Pike and Interstate 64/75 in Lexington, Kentucky, as shown in Fig. 1. The site was deemed ideal for this study since there are many industries (hence presence of trucks) in the area, this route is a major link between Lexington and the interstate highway, and the site operates in oversaturated conditions for the entire PM peak hour. The selected location also minimized the effects of extraneous conditions on vehicle headways. This intersection has 3.6 m (12-feet) wide lanes along Newtown Pike and the grade at the intersection is relatively flat. There is no parking on the street and there is no bus stop at the intersection. Th east approach was not operating when the data were collected.

In order to account for the effects of downstream traffic on the queue of vehicles at the Newtown–Citation intersection, the distance downstream of the stop line was measured and demarcated in 30 m (100 ft) increments. Stakes were placed on the right edge of the shoulder 30, 60, 90, 120, and 200 m downstream. These were used to determine the location of the tail of the downstream queue. The next signalized intersection downstream of the Newtown-Citation intersection was measured to be 300 meters (approximately 1000 feet) downstream.

Headways and intersection layout data collection

Headways were collected during the PM peak period. Headways were measured on Newtown Pike in the northbound (outbound from Lexington) direction. In the northbound direction, there was no right-turning movement at this intersection. Furthermore, the left-turning movement has a dedicated lane. Therefore, the effect of turning movements on the through lanes of this intersection is minimal.

In order to simplify measurements and to lessen the chance of error, data collection was confined to a single-lane. The rightmost through lane was used since it would be closest to the observer during the field measurements. Furthermore, this lane is likely to have the highest proportion of trucks since the entrances to the interstate are both right-hand turns downstream. Also, the right lane is not adjacent to any turning movements.

The intersection is controlled with traffic signal that has a 120 s of cycle length. The allocated green time for the through movement (i.e., the studied discharged traffic) is 80 s.

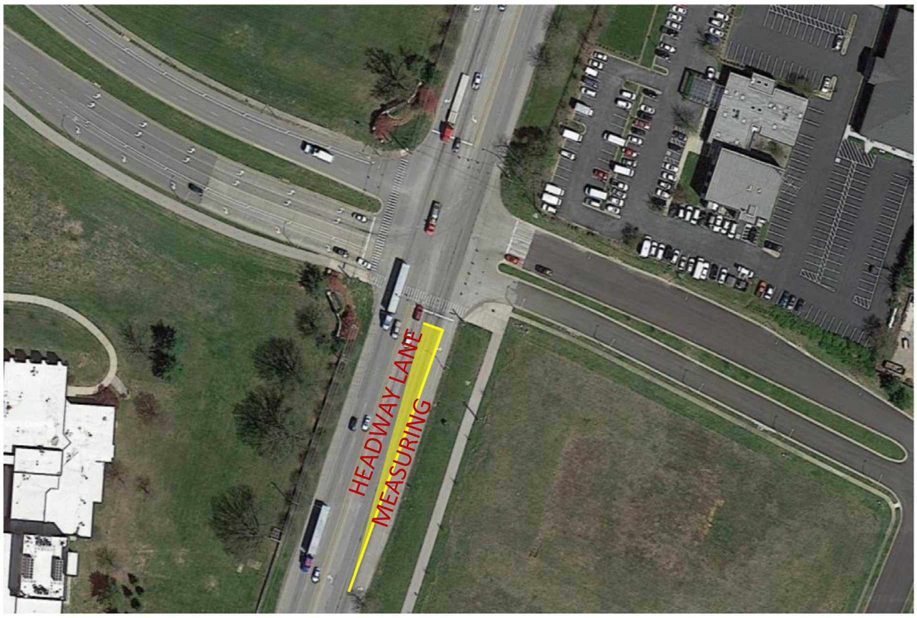

Fig. 1. Location of studied signalized intersection at Newtown Pike and citation BLVD in Kentucky.

Field crew: placement and tasks

A two-person crew was used to record the data. In order to preserve the data, traffic at the intersection was recorded using a video camera. This allowed the data to be analyzed later by watching the video and recording data. The cameraman recorded traffic as it passed the stop line at the Newtown-Citation intersection. The cameraman also noted how far downstream the traffic could proceed at the beginning of each green phase. The queue could often proceed to the back of the queue at the next signalized intersection downstream. However, traffic often queued-up into the Newtown-Citation intersection during the latter part of the green phase as a result of the queue from the downstream signalized intersection.

The second member of the two-man crew was the spotter. The task of the spotter included counting the number of vehicles in the queue in the right lane of Newtown Pike (the subject approach). The spotter counted every vehicle from the first until the last vehicle that came to a stop in the queue resulting from the traffic signal at the Newtown-Citation intersection. When the last vehicle that came to a stop was counted, the spotter communicated this number to the cameraman through a walkie-talkie. The cameraman would then repeat the number to make sure that the audio of the video camera is recorded. This setup later enabled the data analyzer to hear the number on the tape and thus, determine the last vehicle for which to record headway in the subject queue. During oversaturated conditions, when queues were long, the spotter would necessarily need to be within a close distance to the stop line in order to record the number for the last vehicle to actually come to a stop. This made the use of the two-way communication device a necessity.

Another important point that was noticed during the recording of data was that in long queues, a number of vehicles might have very similar descriptions. Therefore, the process of counting vehicles and recording the number of the last vehicle in the queue is more accurate and less prone to errors than simply describing the vehicle. Also, the vehicle queue might be long enough so that there is no practical chance for the last vehicle that stopped at the back of the queue to proceed through the intersection during one green phase. The cameraman would hear a very large number given for the last vehicle that stopped in the queue. Therefore, the fact that a headway for all vehicles in that queue can be recorded would be affirmed by the researcher reviewing the video, as long as the number of vehicles passing through the green indication is less than this number of stopped vehicles in the queue.

Counting headways

The process for counting headways in saturation flow rate as recommended by the HCM 2010, Chapter 9 was used in this study (Transportation Research Board, 2010). The roadway and vehicle reference points used by the HCM 2010 were maintained as well. This was done in order to maintain consistency and to allow the results of this study to be applied to other situations. There was only one deviation from the HCM 2010 saturation flow rate procedure. The HCM 2010 procedure for saturation flow rate recommends using the last vehicle in the stopped queue when the traffic signal turns green. Since the individual headways are important in this research and not just the average headway rate during saturation flow, it was decided to use the headways of all the vehicles that came to a stop, even if they entered the back of the queue after the signal had turned green. This resulted in more data points. Also, these headways would be just as valid as long as all headways used for analysis came from vehicles that had to stop at the back of the queue.

For each cycle, the measurement period began with the passage of the fourth vehicle in the queue. The roadway reference point that was used was the stop line and the vehicle reference point was the rear axle. Vehicles were recorded as their rear axles crossed the stop line. All headways were recorded from the fourth vehicle until the passage of the last vehicle that came to a stop in the queue or until the traffic signal became red for this movement, whichever occurs first.

For measuring the headways, a stopwatch was used that has the capability of measuring lap split times. The headways were recorded using a two-person crew. One person watched the videotape and pressed the lap split button on the stopwatch upon the passage of the rear axle of a vehicle. The second person recorded the lap split time indicated by the stopwatch, which corresponds to vehicle headways in this case. When the headway was for a truck, the person watching the video and operating the stopwatch simply called out "truck" as the lap split button was pushed. The time headway recorder indicated that this headway was for a truck by writing a "T" beside the recorded time. For the purposes of this study, a truck was defined as a heavy vehicle, as is indicated by the Highway Capacity Manual 2010 (Transportation Research Board, 2010).

Analysis of field headways data

Data were recorded for 32 cycles of the traffic signal at the Newtown-Citation intersection. This represents a time period of approximately one hour and five minutes. Table 1 shows information regarding the total number of vehicles that crossed

Table 1
Summary of vehicles passing through the intersection during the study.

No. Cycles	No. Headways	"First Four" Vehicles	No. Vehicles in Green Phase	No. Utilized Headways	No. Car Headways	No. Truck Headways
32	1030	128	82	820	750	70

the stop line during the study and the number of vehicles for which headways could be analyzed. The first four vehicles passing through the intersection during each phase were subtracted from the headway study, as discussed in the experimental setup section, as did vehicles that were forced to significantly slow down or stop in the intersection or on the stop line during the green phase of the Newtown Pike through movement. These vehicles were forced to slow or stop because of the queue resulting from the downstream signalized intersection. This situation occurred during 18 of the 32 cycles. After subtracting the "first four" vehicles and the vehicles that were forced to stop on the stop line because of the downstream queue from the total number of vehicles, the result was the total number of usable headways, 1030 − 128 − 82 = 820.

Out of these headways, 750 were car headways and 70 were truck headways. The distribution of car headways is shown in Fig. 2 while the distribution of truck headways is shown in Fig. 3. It can be seen that both distributions are bell-shaped, similar to the normal distribution, although there are fewer data points for truck headways than those of car headway distribution. Shapiro–Wilk test of normality was applied to both distributions (i.e., car headways and trucks headways). The normality test considered a significance level of $\alpha = 0.05$. The null hypothesis (H_0) states that the headway distribution is derived from the normal distribution. The statistical analysis results are summarized in Table 2. The results show that there was no statistical evidence that any of the headways are normally distributed when all observations are considered. However, if the outliers are removed, the normality tests suggest that truck headways can be normally distributed, while car headways are not.

Truck placement in queue

A count of all vehicles revealed that 18 out of the 128 "first four" vehicles were trucks. In addition, 4 out of these 18 trucks were first in line in the traffic signal queue. Table 3 compares percentages, likelihood of being first in line, and likelihood of being in the first four vehicles in a queue for both passenger cars and trucks.

It can be seen from Table 3, that the likelihood of trucks being in the first four vehicles of their respective queues is 1.7 higher than would be expected based on their share of the traffic. Likewise, the likelihood of trucks being the first vehicle in a queue during the red phase is 1.5 higher than expected. This finding is based on limited number of observations (4 cases) and hence may not be a systematic phenomenon. Intuitively, it might be thought that the occurrence of trucks in queue would be random. However, with the slower acceleration rates of trucks, trucks spend more time approaching a traffic signal, and therefore are more likely to be stopped by the signal turning red. This is a likely explanation of the phenomenon of trucks

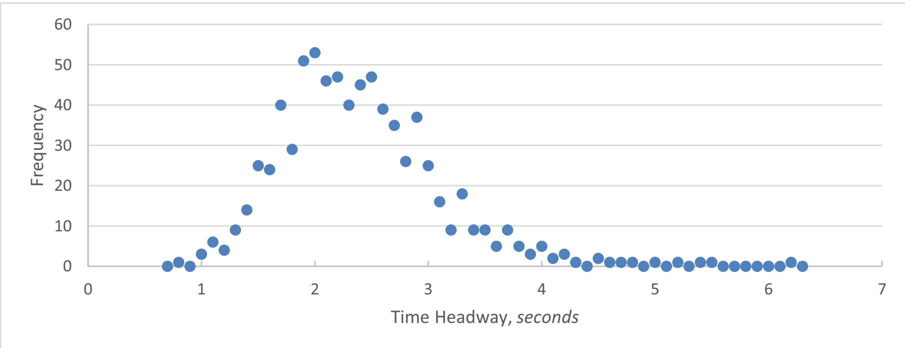

Fig. 2. Observed passenger car headway distribution.

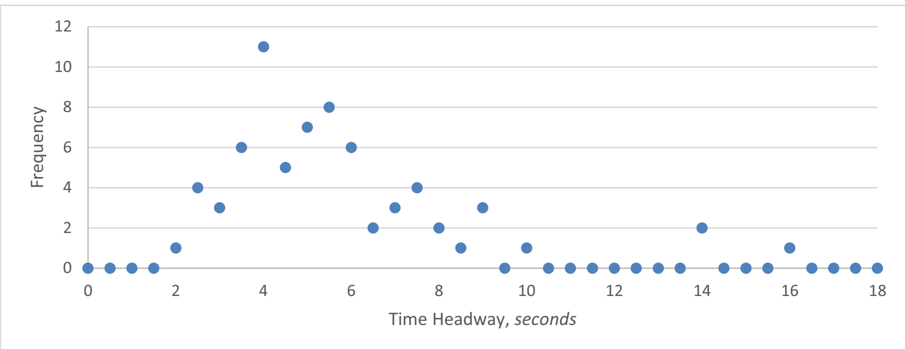

Fig. 3. Observed truck headway distribution.

Table 2
Observed headway distributions test of normality results.

	Car Headways		Truck Headways	
	Outliers Included	Outliers Excluded	Outliers Included	Outliers Excluded
Sample Size	750	734	70	67
Average	2.3437	2.2931	5.3946	4.991940
Standard Deviation	0.69097	0.60032	2.62848	1.826724
Sum of Squares	357.60	264.16	476.71	220.24
Confidence Level	0.95	0.95	0.95	0.95
Skewness	1.043471	0.364255	1.818858	0.560815
p-value	4.88498e-15	0.0000107478	6.22412e-7	0.0659103
W-Confidence Interval	[0.9960: 1.0000]	[0.9959: 1.0000]	[0.9641: 1.0000]	[0.9654: 1.0000]
W-Statistics	0.951264	0.988057	0.848983	0.966281
Conclusion	**Reject H_0** Headways are not normally distributed	**Reject H_0** Headways are not normally distributed	**Reject H_0** Headways are not normally distributed	**Do Not Reject H_0** Headways can be normally distributed

Note: Outliers are headway values beyond 1.5 the Interquartile Range [Q1-1.5xIQ, Q3 + 1.5xIQ]

Table 3
Stream and queue composition characteristics.

	Total		"First Four"		First in Line	
	Number	Percentage	Number	Percentage	Number	Percentage
Cars	940	91.26%	110	85.94%	28	87.50%
Trucks	90	8.74%	15	14.06%	4	12.50%
Total	1030	100%	128	100%	32	100%

having a greater rate of being in the first four vehicles of a queue than being in other spots in the queue at signalized intersections. These findings have important implications to signal timing, lost time estimation, and clearance intervals.

Trucks vs. cars headways comparison

In order to determine the difference between truck headways and car headways, only the valid (or usable) 820 headways were analyzed. Table 4 shows a comparison of the descriptive statistics for car and truck headways from this study. All headway figures are in units of seconds. Table 4 provides a comparison between car headways and truck headways. The average for car headways is 2.34 s while the average for truck headways is 5.39 s. The ratio of average truck headway to average car headway is 2.30. Therefore, one can infer that for each truck in the traffic composition, 2.30 cars could pass the stop line during saturation flow. Thus, using headway observations, the passenger car equivalency, *PCE* , factor for a heavy truck may be taken as 2.3017.

The median headway for both cars and trucks are slightly smaller than the mean. For trucks, the median is 4.95 while the mean is 5.39. The reason for this is that there were a few headways for both cars and trucks that were very much longer than the mean. For instance, the longest car headway was 6.10 s while the fifth longest was only 4.93 s. The longest truck headway was 15.81 s while the fifth longest was only 8.97 s. As expected, trucks had a much greater range of headways and a greater standard deviation. Cars had a much smaller 95% confidence level of the mean. This is mostly due to the fact that many more car headways were recorded than truck headways. At a significance level of 5%, the actual mean of all truck headways is 5.39 ± 0.6267.

Table 4
Descriptive statistics for passenger car and truck headways.

	Car Headway	Truck Headway
Count	750	70
Mean	2.34	5.39
Median	2.27	4.95
Mode	2.19	5.96
Standard Deviation	0.6910	2.6285
Minimum Headway	0.77	1.96
Maximum Headway	6.10	15.81
Headway Range	5.33	13.85
Confidence Level (95%)	0.0495	0.6267

Table 5
Comparison of headways for passenger cars following trucks to those not following.

	Car Headway	
	(Not following a Truck)	(Following a Truck)
Count	693	57
Mean	2.33	2.47
Median	2.26	2.39
Mode	2.19	2.19
Standard Deviation	0.6856	0.7503
Minimum Headway	0.77	1.13
Maximum Headway	6.10	5.44
Headway Range	5.33	4.31
Confidence Level (95%)	0.0511	0.2009

Effect of trucks on following passenger car headways

Comparison was conducted between headways of cars immediately following trucks and those of cars that were not immediately following trucks. Out of the 70 trucks in this study, 56 trucks were followed by passenger cars whose headways were usable. The other 14 trucks were either were followed by trucks, were the last vehicle that passed through the intersection before the red phase, or were followed by a passenger car that came to a stop on the stop line because of the queue from the downstream intersection. Table 5 compares headways of cars not-following a truck with those of cars following trucks.

As can be seen from Table 5, the mean of car headways that were following trucks is 2.47 s. This is greater than the mean of 2.33 s for car headways that were not following trucks. This suggests that some passenger car drivers allow more space ahead when following a truck than when following a smaller vehicle. This would indicate that trucks not only take up more space on the road, but they also impact headways of following vehicles. However, the difference in means is only 0.14 s. This is significant only at the 10% confidence level.

Microscopic simulation model

At the microscopic level, the *PCE* value depends on the behavior of trucks (both static and dynamic characteristics) and the behavior of the truck's drivers and the following driver. The behavior of drivers is dependent on their "sensitivity" and reaction time. The reaction time and sensitivity in return are influenced by road topography (upward, downhill, level) and the traffic stream heterogeneity (friction between trucks and passenger cars). The impact of the topography is intuitive; trucks are more obstructive on upward grades than on flat road. However, the influence of those factors (trucks characteristic, driver sensitivity, topography, and stream heterogeneity) are interdependent from the sense that one can see that the truck driver sensitivity changes if they are on a flat road versus upward or downhill. Therefore, the calibration of the micro-model was performed to closely replicate the collected field data and observed traffic patterns.

Field observations were used to build and calibrate a microscopic simulation model for the network described earlier. The model was then used to evaluate the impact of various levels of congestion and truck concentrations on the estimation of *PCE*. PTV VISSIM multimodal microscopic simulation environment is used in this research. This simulation testbed provides a wide range of possible parameters to be modified and adjusted in order to replicate real-life conditions. In this research, different calibration criteria were used to assure the applicability of the model before different scenarios are tested. These criteria will be discussed in detail at later stage. It is worth mentioning that multiple independent runs were executed to account for normal stochastic variations. It should be noted that the headways data collected form the simulation environment were treated in a similar manner to the observed ones (i.e., the first four vehicles per cycle were ignored, and only queued vehicles were considered).

Microscopic model calibration

The Existing study area along with the observed traffic data and headways were used to calibrate the microscopic simulation model. The first step was to code the existing geometric layouts, speed limits and signal timing parameters within the simulation parameters (Shaaban et al., 2019). The next step was fine-tuning several parameters and vehicle characteristic so that the observed traffic volumes and headways are replicated (Ghanim et al., 2014). In particular, the calibration process verifies if the number of observations (i.e., counts), the average headways values and the headway distributions of different traffic patterns are similar or not.

As indicated earlier, there were several adjusted parameters and distributions through trial and error process until the simulated results were comparable to the observed one. These parameters can be summarized as follow:

- Trucks' Power and Weight distribution
- Trucks' Desired Acceleration Distributions
- Desired Speed Distributions for Cars and Trucks
- Driving behavior Parameters
- Traffic Demand
- Vehicular Mixture

The use of microsimulation environment is widely used to assess several traffic engineering applications (Ghanim and Abu-Lebdeh, 2015; Ghanim and Shaaban, 2018a). Once the model is calibrated, it is often used to simulate and evaluate different scenarios that are derived from the calibrated base model (Ghanim et al., 2013; Abu-Lebdeh et al., 2016). The calibration process is performed by comparing one or more performance measures as collected in the field against those resulted from the simulation environment testbed. The selected performance measures depend on the scale and the nature of the issue being addressed. The calibrated parameters are related to the traffic demand, traffic mixture, car-following models, and speed profile (Chu et al., 2003; Fellendorf and Vortisch, 2010; Punzo et al., 2014).

Table 6 and Table 7 summarizes the different values for the calibrated parameters. It should be noted that the traffic demand and traffic mixture that lead to the results shown in Table 7 are 2100 vehicles per hour and 8.53% (70 trucks out of 820 vehicles), respectively.

The results show that the difference between observed and simulated headways are within 10% of the observed values, ranging between 1.4% and 6.5%for most of the headway types. Which is an indication that the simulation model is well-

Table 6
Summary of field headway observations.

	All Traffic	Cars	Trucks	CFC	CFT	TFC	TFT
Valid Headways	820	750	70	693	57	61	9
Average	2.60	2.34	5.39	2.33	2.47	5.47	4.91
Std. Dev	1.3215	0.6910	2.6285	0.6860	0.7436	2.7655	1.3900
Minimum	0.77	0.77	1.96	0.77	1.13	1.96	3.5
Maximum	15.81	6.10	15.81	6.10	5.44	15.81	7.29
Range	15.04	5.33	13.85	5.33	4.31	13.85	3.79
Number of Cycles			32				
Total Headways			1030				
"First Four"			128				
Cars in "First Four"			110				
Trucks in "First Four"			18				

Table 7
Summary of simulated headway observations.

	All Traffic	Cars	Trucks	CFC	CFT	TFC	TFT
Valid Headways	862	793	69	736	57	62	7
Average	2.51	2.25	5.47	2.18	3.17	5.53	4.95
S. Dev	1.4167	0.9821	2.1214	0.9397	1.0610	2.2272	0.4727
Minimum	0.82	0.82	1.97	0.82	2.10	1.97	4.14
Maximum	11.23	10.59	11.23	10.59	7.88	11.23	5.69
Range	10.41	9.77	9.26	9.77	5.78	9.26	1.55
Number of Cycles			32				
Total Headways			1035				
"First Four"			128				
Cars in "First Four"			105				
Trucks in "First Four"			23				

Table 8
Summary of statistical tests: comparison of the average headways.

Headway Type	Observed Headway	Simulated Headway	Absolute Difference	*t - value*	$t_{\propto/2}$
All Traffic	2.60	2.51	0.09	1.5126	2.5787
Cars	2.34	2.25	0.09	2.0050	2.5790
Trucks	5.39	5.47	0.08	0.2414	2.6111
CFC	2.33	2.18	0.15	*3.2878*	2.5792
CFT	2.47	3.17	0.70	*3.8430*	2.6185
TFC	5.47	5.53	0.06	0.1581	2.6161
TFT	4.91	4.95	0.04	0.0893	2.8982

Note: Underlined number indicates that H_0 can be rejected calibrated to replicate the real-life conditions. However, further statistical tests were performed to compare each type of the seven different headways types, namely the t-test, as summarized in Table 8. The confidence level was set to 99% (α is 0.01). It was also assumed that both headway groups have the same variance. The H_0 hypothesis was evaluated against the H_1.

After comparing the mean, the traffic headway distributions for observed and simulated traffic are plotted (relative and cumulative frequency), as can be seen in Fig. 4 and Fig. 5. The figures show that the headways distributions are very close to each other, with similar peak. Although the simulated distribution seems to be slightly shifted to the left, the difference is only 0.1 s between the observed and simulated means (less than 4% of the averaged observed values).

Simulated scenarios

The calibrated microscopic model is considered as the base model. The additional simulation experiments have two dimensions, traffic demands and truck percentages. For the first dimension, traffic demand was incrementally increased from 1000 to 3000 vehicles per hour (approximately 50–140% of the base demand), covering unsaturated and saturated conditions. Since data were collected for through traffic at the right-most lane, this demand level is true for the subject and the downstream intersections. At this level of demand, traffic queues grew with time and stop-and-go flow persisted for longer time and covered longer distance along the signalized approaches. Interference from downstream queues was more apparent. The tail of ''platooned" traffic was monitored visually as it was the case with the filed observations.

As for the second dimension of the experiments, truck percentages ranges between 0% and 40% with an incremental increase of 5%. The initial simulation-based assessment indicated that increasing the percentage of trucks beyond 40% did not appear to impact the estimate of *PCE*, and observing truck percentages beyond the 40% is not practical as it is not often found in real-life.

With respect to the traffic signal parameters, the green time and cycle length are kept the same for all the tested scenarios, as to the base level model, based on the field observation.

Simulation-based traffic headways trends

The total of 189 scenarios were developed, by combining the 21 different traffic demand segments combined with 9 different percentages of trucks. At first, headways were classified based on the following vehicles cars (C) and trucks (T), regardless of the preceding vehicle. Furthermore, each one of these two groups were classified based on the preceding vehicle,

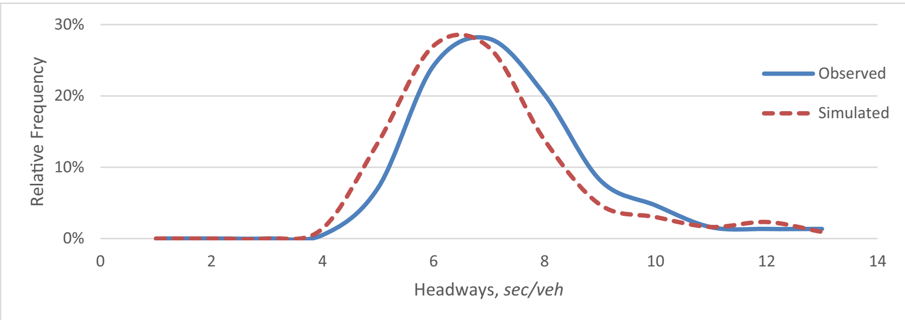

Fig. 4. Observed vs. simulated traffic headway distribution.

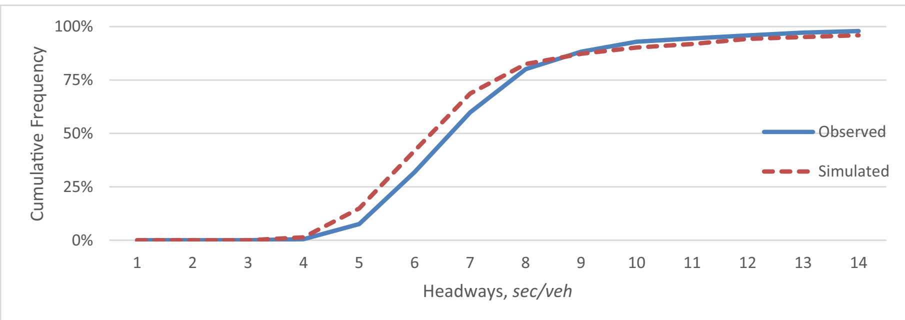

Fig. 5. Passenger car headway distribution.

which resulted in the total of four different groups car following car (CC), car following truck (CT), truck following car (TC) and truck following truck (TT).

Fig. 6 shows that the average headway remains constant in general regardless of the demand increase. It can also be noticed that there is some variation in headways when the demand is relatively low. This observation is associated with the queue size at the beginning of the cycle. Due to the low demand, the chance for queue formation is low, and therefore more variation on saturated headways can be noticed. This observation is more significant when trucks are involved (i.e., CC and CT headways). As for CC headways, the average headways are almost constant, regardless of the demand level.

On the other hand, Fig. 7 shows the average headway trends against the increase of trucks percentages. The figure shows that trucks headways average tends to increase slightly before decreasing as the percentage of trucks increases, while the cars headways keeps increasing continuously. These observations are consistent regardless of the type of preceding vehicles. It is worth mentioning that a similar trend is observed for the impact of increasing the percentage of trucks on headways for basic freeway sections and multilane highways (Transportation Research Board, 2010; Transportation Research Board, 2016), where the passenger car equivalency factor, E_t value decreases as the percentage of trucks increases, regardless of the length and the slope of the freeway/highway segment. For instance, for a freeway section between 3% and 4% upgrade slope and a length of 1.5 miles, the E_t value associated with 2% trucks is 4.0, while the value associated with 25% trucks is 2.5.

Development of passenger car equivalency factor for trucks (PCE)

The simulation results were processed. As indicated earlier, for each scenario (i.e., combination of traffic demand and trucks percentage), the average of 10 simulation runs with different random seed is calculated for each cycle, and for the total of 32 cycles. Note that the warm-up period is taken as 30 min before the data were collected.

The first step in analyzing the data was to calculate the average number of headways per cycle, in order to verify that the sample size of headways is adequate to draw conclusions. This will assure that the estimations are not biased. Table 9 summarized the average number of valid headways per cycle. Based on the results summarized in this table, scenarios with traffic demand that is less than *1400 veh/hr* were excluded from calculating the equivalency factors (*PCE*).

Passenger cars equivalency factors (*PCE*) for trucks were calculated based on Equation (1) and summarized in Table 10. The results show that the lowest PCE_t, averaged across all traffic demand, has a minimum value of 2.13. This value is slightly higher than the HCM 2010 recommended value, which is consistent with the literature review findings. The averaged *PCE* values were plotted against the percentage of trucks in Fig. 8. The figure shows that as the percentage of trucks increases,

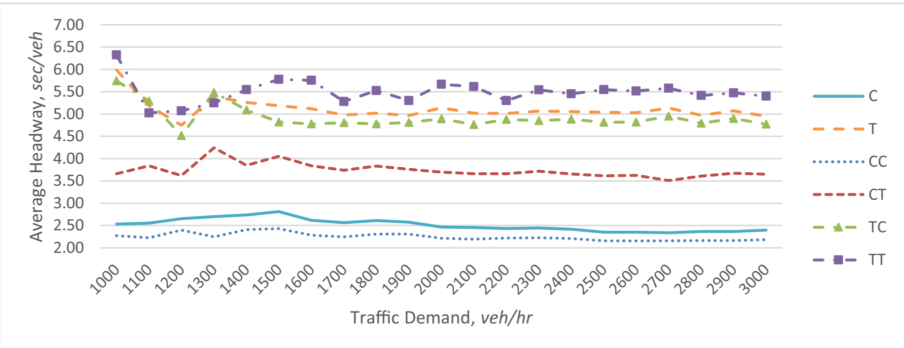

Fig. 6. Impact of demand increase on average headways.

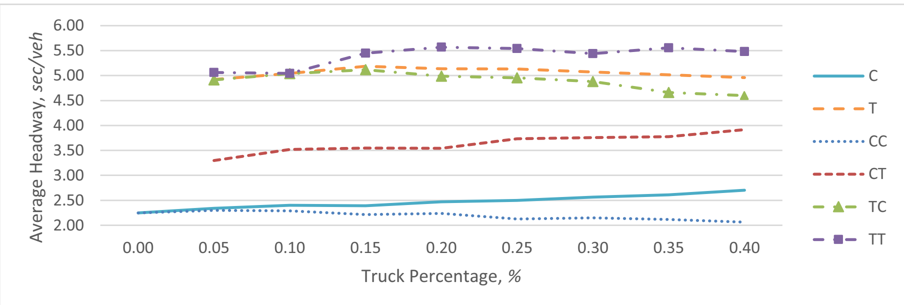

Fig. 7. Impact of truck percentage increase on average headways.

Table 9
Average number of valid headways per cycle for each scenario.

Traffic Demand	Truck Percentage, % 5%	10%	15%	20%	25%	30%	35%	40%
1000	1.2	0.8	1.1	1.9	1.4	2.4	2.5	1.9
1100	1.4	1.4	1.4	1.5	3.8	2.3	3.1	3.1
1200	2.3	1.8	2.3	2.9	3.7	3.5	4.5	3.8
1300	2.0	2.0	3.6	4.3	5.9	5.0	6.5	6.6
1400	3.3	4.3	5.0	6.3	9.1	7.8	10.7	13.2
1500	4.3	6.0	4.3	8.2	11.6	17.5	18.2	20.1
1600	5.4	5.7	6.8	11.3	22.9	21.6	20.3	20.5
1700	6.3	7.1	11.7	19.8	22.7	21.7	20.8	19.7
1800	8.9	10.0	14.9	20.8	23.7	22.3	20.3	19.8
1900	8.4	11.6	23.9	23.0	22.3	22.9	20.3	20.0
2000	9.9	23.6	24.2	24.7	22.8	21.0	20.4	19.8
2100	18.4	26.7	25.6	24.4	22.5	21.3	21.5	19.1
2200	25.1	29.1	27.3	25.0	23.2	22.3	20.0	20.3
2300	30.5	29.2	26.3	25.3	23.1	22.3	20.3	19.4
2400	31.7	28.7	26.1	23.6	23.6	22.0	20.6	20.0
2500	32.3	28.6	27.3	25.7	22.1	21.7	21.0	20.5
2600	33.5	28.3	27.2	25.8	23.1	21.1	20.5	20.3
2700	31.2	29.2	27.3	24.6	23.4	22.3	20.7	19.9
2800	32.0	29.5	26.3	24.9	23.0	22.3	20.8	19.4
2900	32.2	27.6	26.8	25.6	22.2	22.5	20.5	19.3
3000	31.7	28.1	26.0	23.3	22.3	22.0	21.4	20.5

Table 10
Summary of large trucks passenger car equivalency (*PCE*) values.

Traffic Demand	Truck Percentage, % 5%	10%	15%	20%	25%	30%	35%	40%
1400	1.96	1.91	2.15	2.41	2.17	2.25	2.49	2.16
1500	2.13	2.36	3.23	2.79	2.22	2.23	2.23	2.07
1600	1.74	1.76	2.91	2.48	2.32	2.38	2.34	2.23
1700	1.71	2.06	2.27	2.09	2.24	2.22	2.08	2.13
1800	2.15	2.36	2.16	2.13	2.23	2.13	2.21	2.16
1900	2.06	2.06	2.19	2.27	2.27	2.17	2.09	2.07
2000	2.36	2.24	2.26	2.21	2.29	2.23	2.26	2.27
2100	2.29	2.25	2.40	2.37	2.43	2.20	2.26	2.31
2200	1.98	2.05	2.28	2.08	2.19	2.24	2.09	2.17
2300	1.99	1.98	2.08	2.01	2.12	2.07	2.04	2.15
2400	2.16	2.23	2.13	2.18	2.15	2.05	2.09	2.07
2500	2.34	2.30	2.46	2.18	2.28	2.36	2.24	2.20
2600	2.19	2.14	2.26	2.25	2.26	2.24	2.33	2.21
2700	2.32	2.53	2.53	2.35	2.28	2.35	2.31	2.32
2800	2.49	2.38	2.20	2.28	2.23	2.33	2.20	2.24
2900	2.18	2.43	2.32	2.25	2.33	2.32	2.35	2.35
3000	2.17	2.29	2.29	2.40	2.33	2.26	2.16	2.17
Average	**2.13**	**2.20**	**2.36**	**2.28**	**2.25**	**2.24**	**2.22**	**2.19**
Standard Deviation	**0.20**	**0.20**	**0.29**	**0.18**	**0.07**	**0.09**	**0.12**	**0.08**

the *PCE* value starts to increase from the value of 2.13 that is associated with 5% of trucks, up to a certain level (15% of trucks), before the *PCE* value starts to decrease almost linearly as trucks percentage goes beyond 15%, till it reaches the value of 2.19 when the percentage of trucks is 40%.

In general, the results show that for all cases, the *PCE* was more than the HCM 2010 recommended value of 2.0. Furthermore, the average *PCE* value based on these results was 2.23. This suggests that if a single value shall be used, then a recommended value of 2.30 might be considered, based on field observations.

Intuitively, it is expected that the *PCE* value goes up starting with uncongested conditions to congested conditions. When traffic demand gets to congestion, and due to the fact that there is higher density and uniformity in traffic, then the *PCE* values become less sensitive to the increase of trucks percentages when a significant proportion of trucks are mixed with the traffic stream. For instance, if the traffic stream has only one truck, drivers of passenger cars and the driver of the truck tend to be cautious by leaving enough gap between the truck and the other vehicles.

The way the *PCE* value changes with the percentage of trucks in the traffic stream is neither obvious nor straightforward. When the percentage of trucks in the traffic stream is low, truck drivers tend to be more sensitive to the flow conditions of

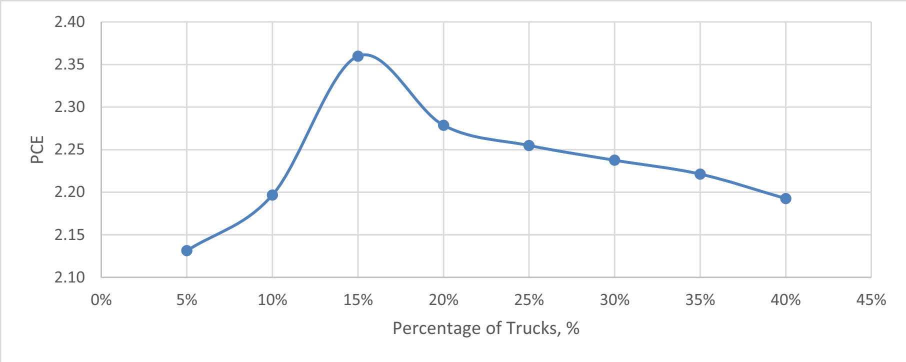

Fig. 8. Impact of truck percentage increase on *PCEs*

the traffic stream. More specifically, they become more sensitive to the behavior of smaller cars' drivers. Simply because the drivers of smaller vehicles, by virtue of the nature of their vehicles (i.e., acceleration, deceleration, lane change behavior), are more nimble and quicker than trucks. As such truck drivers are more alert and more "sensitive" so that they can react in time and/or apply the appropriate level of deceleration. From the perspective of smaller cars, they have the room to leave larger space headways when they are following a truck compared what they usually leave when following a passenger car. However, as the percentage of trucks in the traffic stream increases, the sensitivity of truck drivers become less because now there is some level of truck dominance, or significant enough presence of trucks in the traffic stream that the momentum of flow is more shaped by trucks themselves. In this case the traffic stream is less sensitive to the individual behaviors of smaller cars since their percentage is lower and the flexibility of controlling space headways is reduced. Under those conditions truck drivers tend to be less sensitive since the presence of a higher percentage of trucks in the traffic stream makes condition more predictable as trucks are similar in behavior as their own.

Therefore, once more trucks are observed, those gaps become less, which suggests that the drivers have accepted the fact that they are surrounded by trucks, and hence there is no point of leaving an extended gap. Another potential factor is the potential impact of trucks on speed and lane changing maneuverability. However, these factors require more investigations that can be investigated at later stages.

Summary and conclusion

This research used headways to characterize and evaluate the operational characteristics of heavy vehicle, and contrast that to passenger cars under oversaturated interrupted conditions. Some of the results reinforce already established knowledge. It is recommended that the *PCE* value ranges from 2.1 to 2.35 based on the percentage of trucks. However, if a single value shall be assigned then a value of 2.25 is proposed based on the results of this research.

The results showed that trucks are disproportionably more likely to be first in queue and in the first four vehicles of a queue, than they are to be in other positions. Trucks were found to increase headways of following passenger cares. It can be inferred form the results that trucks are less likely to violate the red indication of a traffic signal because of the slow speed of the truck and the longer length of the truck.

The same methodology described in this study could be performed at other locations in order to discover differences between results from different locations and to increase confidence in the results. Also, more data could be recorded for the same intersection in order to achieve more data points. A larger database of headways could be built that would facilitate the understanding of differences between car headways and truck headways. The same procedure could be repeated in the left lane of the intersection to see if there are any differences in headways between left and right lanes of an intersection.

Another important direction for future research is to quantify a passenger car equivalency headway value for the "first four" vehicles in the queue. Since there seems to be a greater likelihood for trucks to appear as one of the first four vehicles in a queue at a signalized intersection, and since trucks require a longer time to accelerate from a stop than cars do, it would be important to quantify the ratio between truck headways and car headways in the first four vehicles of a queue after the signal has turned green. Truck headways in this case would likely be greater than the truck headways studied in this research since, in the "first four" vehicles, trucks will not have had enough time to accelerate from a stop. It is likely that trucks in the "first four" vehicles of a queue at a signalized intersection have a greater impact on lane capacity than trucks elsewhere in a queue.

As the percentage of trucks in the traffic stream increases, the *PCE* value goes up, but then there comes a point where the *PCE* value actually starts decreasing. At this point, the percentage of trucks becomes significant enough in the traffic stream so that large presence of trucks introduces uniformity and predictability, which reduces the sensitivity to the drivers of tracks.

Based on the result that headways of passenger cars immediately following trucks are slightly longer than other passenger car headways, it would be relevant to study the effect of lead-vehicle size on driver following behavior. More data should be collected for cars immediately following trucks in order to better understand this relationship.

While it is reasonable to assume that a heavy truck is operationally equal to at least 2.25 passenger cars during oversaturated interrupted flow conditions. However, more data from additional sites across the nation should be collected and examined before the results of this research can be generalized and used in capacity analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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