DEVELOPMENT OF PASSENGER CAR EQUIVALENCY VALUES FOR HEAVY VEHICLES FOR PROTECTED LEFT-TURN MOVEMENTS AT SIGNALIZED INTERSECTIONS

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

The Highway Capacity Manual (HCM) provides methods to account for the impact of heavy vehicles in the operational assessment and design of signalized intersections. However, the overall impact of heavy vehicles on the saturation flow rate, an important parameter used to calculate capacity, is not fully understood, particularly in exclusive left-turn lanes, where little research has been conducted. This research explores the limitations of the HCM default values, procedures, and recommendations regarding heavy vehicles in protected exclusive left-turn movements at signalized intersections, and makes improvements for use by the traffic engineering professional community. Passenger car equivalency (PCE) values of 1.66, 1.93, and 3.01 were developed for small, medium, and large trucks, respectively, for protected exclusive left-turn movements at signalized intersections. These PCE values, based solely on field data collected in Fargo, North Dakota, are incorporated into a revised equation used to determine the heavy vehicle adjustment factor, f_{HV}.

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DEDICATION

This thesis is dedicated to my wife, Susan, who has provided the love and support I needed to complete this thesis. I know you will always provide the same support for any challenge I encounter. This thesis is also dedicated to my parents, Dan and Lida, who have been there for me whenever I needed help. It was by your example that I have learned how apply myself in academics and life. Your love and support has been a constant source of motivation for me.

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LIST OF ABBREVIATIONS

Ave .... Avenue

FHWA .... Federal Highway Administration

HCM.. Highway Capacity Manual

Hr .... Hour

Lbs.. Pounds

LDT .... Light-duty truck

Ln .... Lane

LOS .... Level of service

LT.. Large truck

MT... Medium truck

NCHRP.. National Cooperative Highway Research Program

PC.. Passenger car

PCE .... Passenger car equivalency

PCU .... Passenger car unit

RV .... Recreational vehicle

S .... South

Sec... Seconds

SLT.. Start-up lost time

St .... Street

ST .... Small truck

SUV... Sport-utility vehicle

SW... Southwest

US.. United States

Veh .... Vehicle

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1. INTRODUCTION

The saturation flow rate is an important parameter used to determine the capacity of a lane or lane group. The saturation flow rate varies at all lanes and intersections depending on a number of geometric, geographic, and operational factors. Many research studies have been done on saturation flow rates at signalized intersections. Of these studies, some focus on related passenger car equivalency (PCE) values (Branston and van Zuylen 1977; Sosin 1980; Molina et al. 1987; Stokes 1988; Cuddon and Ogden 1992; West and Thurgood 1995; Benekohal and Zhao 1996; Rahman et al, 2003; and Washburn and Cruz-Casas 2010), but still there is no consensus on how to adequately address the impact of different types of heavy vehicles, and research for left-turns is particularly limited. As the research conclusions on this topic vary widely, the determination of PCE for different types of heavy vehicles requires reexamination.

The objective of this research is to determine PCE values for three types of heavy vehicles in left-turn lanes of signalized intersections during protected signal phasing for calculation of adjusted saturation flow rates. Additionally, it was investigated how current methods for determining saturation flow rates could be improved upon for exclusive left-turn lanes, particularly those with high percentages of heavy vehicles.

1.1. Background

Left-turn movements are a major cause of delays at intersections. Traffic engineering researchers are aware that heavy left-turn movements impair performance of intersections. Innovative geometric designs such as the roundabout, diverging diamond, and offset left-turn lanes are among the solutions used to mitigate the conflicts and delays that left-turn movements cause. However, these innovative designs are not always an option due to space constraints, cost, etc., and the majority of urban signalized intersections in the United States (US) still operate with traditional geometric designs. Therefore, it is imperative that current operations analysis and design recommendations properly account for the existing and projected traffic flows, so that signalized intersections can accommodate traffic optimally, especially when a high percentage of heavy vehicles is expected.

The left-turn lane does not typically receive the same number of vehicles as the through lane(s) at a signalized intersection. However, since left-turning vehicles must find appropriate gaps to complete their maneuvers, and are associated with more conflict points compared to that of through and right-turn movements, a designated protected signal phase is often required to accommodate left-turn movements at signalized intersections when left-turn volumes become quite perceptible. The need of additional signal phases increases lost time due to additional change intervals and also typically increases the control delay for all movements at an intersection. As a result, an improper signal plan or intersection geometric design for left-turn movements can also increase delays and decrease the level of service (LOS) for other movements at an intersection.

Saturation flow rate is a parameter used to determine the capacity of a lane or lane group. Saturation flow rate is defined in the Highway Capacity Manual 2010 (TRB 2010) as "*the equivalent hourly rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions, assuming that the green signal is available at all times and no lost times are experienced.*" It is naturally an "adjusted" rate because various conditions present at each intersection are applied to a base saturation flow rate as an adjustment. Used in combination with lost times (i.e. start-up and clearance lost times), as well as green phase duration, the capacity or projected capacity of a lane or lane group can be determined. Therefore, the saturation flow rate directly impacts the capacity of a lane group. If the demand nears or exceeds the capacity, then the lane group cannot accommodate the traffic effectively, which leads to increased delays and a decreased LOS.

Because of their size, length, and decreased power-to-weight ratio, heavy vehicles can have a tremendous impact on the operations of a signalized intersection. Not only do they take up more space and have slower acceleration rates, but they can also negatively affect the operations of vehicles around them. Each heavy vehicle at an intersection decreases the capacity of the lane group at an intersection. The calculation of capacity, as it relates to the v/c ratio in the HCM, directly influences the design of signal plans and the determination of delay. Therefore, if not properly accounted for, heavy vehicles will introduce unaccounted for delays, leading to decreases of LOS.

There are two options to determine saturation flow rates: estimating it with an equation (using adjustment factors to reflect local geometric, traffic, and environmental conditions), or measuring the prevailing saturation flow rate directly in the field. The Highway Capacity Manual 2010 (TRB 2010) has recommended procedures for both options.

Traditionally, traffic composition is classified into two groups for capacity analysis: passenger cars and heavy vehicles. With emerging data collection technologies such as infrared laser, magnetic, radar, and video detection that can more accurately differentiate between different heavy vehicle sizes by using length-based vehicle classification (Minge 2010), the HCM needs to have an f_{HV} (heavy vehicle adjustment factor) equation that can accommodate different heavy vehicle sizes instead of grouping all heavy vehicles into one class.

1.2. Problem Statement

Recent studies (Washburn and Cruz-Casas 2010; Dowling et al. 2014) show that the impact of heavy vehicles in through movements at signalized intersections is being underestimated, leading to an overestimation of capacity. This overestimation of capacity is more problematic when there are more heavy vehicles in the traffic stream. Additionally, there is little research on the impact of heavy vehicles making protected left-turns at signalized intersections. Moreover, the impact due to different types of trucks needs to be better understood in order to accommodate modern data collection technologies.

1.3. Objectives

The primary objective of this research is to determine the impacts of three different types of heavy vehicles making protected left-turns at signalized intersections so that the impacts can be adequately calculated in the HCM's adjusted saturation flow rate equation. Additionally, the results of this study are compared to the HCM methods for determining saturation flow rates. An improvement on the recommended techniques is proposed specific to exclusive left-turn lanes making protected movements.

1.4. Scope

The scope of this research is limited to determining the operational impact of heavy vehicles making protected left-turns from exclusive left-turn lanes at signalized intersections. Only left-turns with high percentages of truck movements were considered in order to acquire the adequate field data for analysis. Ultimately, three left-turn movements in Fargo, North Dakota, which had an estimated metropolitan population of about 223490 in 2013, according to the US Census Bureau (US Census Bureau, Population Division 2014), were chosen for this study. All three locations had observed higher percentages of heavy vehicles due to the proximity of the intersections to truck stops. Two of the movements were under protected-permitted signal phasing at the same intersection, but time headway data was only collected during the protected movements. The third location was at a separate intersection and had a fully protected movement with dual left-turn lanes. The time headway (hereafter referred as headway) of each vehicle as they proceeded from a standing queue during the green signal phase were of particular interest in order to determine the saturation flow rate of the lane.

1.5. Organization of Thesis

In Chapter 2, a background on saturation flow rate, current practice, and relevant research related to this study is described. In Chapter 3, the methodology for study approach is described as well as the data collection procedures. In Chapter 4, a detailed data analysis is conducted, as well as the results and validation. In Chapter 5, a discussion of the results is made, and how the findings add to the body of knowledge on the topic of saturation flow rate and heavy vehicles. Recommendations are also made on how the results can be applied by professionals in the field of traffic operations analysis. In Chapter 6, conclusions and other findings are summarized.

2. LITERATURE REVIEW

A literature review was conducted to understand the state of practice in regards to incorporating the effects of heavy vehicles making left-turns at signalized intersections. The HCM (TRB 2010) is generally accepted as the primary guide for operational design of signalized intersections. Therefore, most researchers compare their results to the HCM recommendations or correlate their methodology with the traffic theory, capacity, and level of service (LOS) concepts presented in the HCM. A thorough review of the HCM in regards to capacity and saturation flow rate at signalized intersections was conducted, and how heavy vehicles are accounted for in those determinations. Further review was conducted to seek out research studies that have analyzed saturation flow rate, left-turns, heavy vehicles, and PCE values at signalized intersections.

2.1. Background of Saturation Flow Rate and Passenger Car Equivalency Values

A review of literature shows that the origin of the term "saturation flow" is most synonymous with the research conducted by Webster (1958), in which the traffic signal departure process was modeled with a waiting queue which does not completely clear by the end of the green signal phase. This departure process begins with a flow rate of zero at the green indication and accelerates up to a point where the departure rate becomes steady until the yellow phase where the flow rate decelerates back to zero. The steady departure rate is deemed as the saturation flow rate. The terms "effective green" and "lost time" were also implemented in the model and are used to calculate saturation flow. Supplemental observations showed that one heavy or medium sized commercial vehicle was equal to 1.75 passenger car units (PCU) and one bus was equal to 2.25 PCU.

A deeper look into the history of “saturation flow” shows that the roots of this term trace at least as far back as 1940’s, where Clayton (1941) developed the term “saturation density,” defined as the rate in which “*vehicles are running as close together as possible*” and “*they will eventually be entering the junction at a uniform rate per traffic lane.”* Then, Greenshields et al. (1947) presented a famous work on departure headways, showing that after the 5^{th} vehicle in the queue, passenger cars on a through movement began to enter the intersection with similar headways. It was also found that the effective headway of a truck or bus was equivalent to 1.5 times that of a passenger car. This included the findings that the headway of a passenger car following a truck was greater than the headway of a passenger car following another passenger car. This “headway ratio method,” as it later became known, has since become one of the most popular methods to determine passenger car equivalency (PCE) values.

In 1965, the second edition of the HCM (HRB 1965) provided transportation practitioners with a step-by-step approach to determining the capacity of an approach at a signalized intersection. A load factor based on level of service and maximum service volumes was used to determine the unadjusted capacity of a signalized intersection approach (i.e. vehicles per hour of green). Then, applying the fraction of total cycle time devoted to the green signal as well as any necessary adjustment factors will yield determination of actual service volume of the approach. It states, “*Passenger car equivalency values are not used in intersection capacity computations; rather, direct adjustment factors are provided. However, one truck can be considered as equivalent to a minimum of two passenger cars at intersections.*”

According to Jack A. Hutter in a discussion of a report presented by Sofokidis et al. (1973), users of the 1965 HCM “*expressed various degrees of dissatisfaction with a number of the adjustment factors utilized in the analysis technique, with specific reservations regarding the* *concept of level of service, load factor, and peak hour factor,*" and "*a number of critics have maintained that other methods utilizing measures such as lane headway, saturation flow, or delay produce more accurate results.*" The next edition of the HCM in 1985 made use of an equation to determine saturation flow rate, including a base saturation flow rate and a number of adjustment factors to account for non-ideal conditions such as heavy vehicles. It is this equation that remains the primary method in determining saturation flow rate and thus, capacity. To this day, much research has been conducted refining this equation, which is presented section 2.2.2.

A major update to the HCM1985 was released in 1994 (TRB 1994), which contained the most recent change to the PCE value at signalized intersections, recommending a value of 2.0. This value was changed as a result of responses to surveys which indicated that the PCE value of 1.5 was lower than observed (Strong 1994). The recommended PCE value has remained unchanged since 1994.

2.2. Current Treatment of Heavy Vehicles at Signalized Intersections

The HCM is the primary source document for capacity and quality of service for the operations of streets, highways, pedestrian, transit, and bicycle facilities. It consolidates the latest research into one manual to provide transportation practitioners and researchers state-of-the-art methodologies and recommendations for assessing the performance of transportation facilities. It is updated intermittently to ensure that practitioners have access to the latest research results. The next edition of the HCM (6^{th} edition) is due for release in 2016.

2.2.1. Calculating Capacity at a Signalized Intersection

Before explaining the processes of determining saturation flow rate, which is the key parameter used in this research, this section aims to explain how saturation flow rate is used by traffic engineering researchers and practitioners. The capacity of an intersection is an important performance measure and may be more commonly known to those who only have a cursory understanding of intersection performance. The HCM defines the capacity as "*the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions.*" It is a flow rate that can be reasonably expected under repeated conditions of sufficient demand. It is not the maximum possible flow rate ever encountered as is sometimes believed. The capacity is directly related to the saturation flow rate and is also a function of signal phase duration, cycle length, start-up lost time, and clearance lost time. Capacity, as it relates to the v/c ratio in the HCM, directly influences the design of signal plans and the determination of delay and LOS. More details on the computation of capacity as well as other uses of saturation flow rate can be found in the 2010 edition of the Highway Capacity Manual (TRB 2010).

2.2.2. Estimation of Saturation Flow Rate

The base saturation flow rate, which occurs under ideal geometric and operational conditions, is generally assumed to vary with regional population, though this assumed base saturation flow rate has fluctuated over the years in the HCM, and there are a variety of factors that will decrease (or increase) this number. The value of the base saturation flow rate continues to be debated or argued in traffic engineering professional and research community. Some of the known influencing factors known to affect saturation flow rate such as area population, geographic region, posted speed limit, traffic pressure, and others are not fully understood. *NCHRP Report 599* (Zegeer et al. 2008) shows that base saturation flow rate varies considerably across the US, typically between 1510-2190 pc/hr/ln, and that the default value is a most closely correlated with population. The base saturation flow rate essentially accounts for any and all factors not already accounted for with adjustment factors. Although there is not a firm grasp on what the default base saturation flow rate should be, the HCM considers new research studies when considering an accepted value (TRB 2010). The most recent edition of the HCM (HCM2010) recommends a local calibration of base saturation flow rate, but if that is not available, it does provide a default value of 1900 pc/hr/ln for metropolitan areas with population greater than 250000 people. Otherwise the default value is 1750 pc/hr/ln. This research study does not seek to change the base saturation flow rate, but some conclusions about it are made in regard to the three sites studied. The equation for the adjusted saturation flow rate is shown below. Note that two of the incorporated adjustment factors are presence of heavy vehicles and left-turns.

$$S = S_0 \, N \, f_W \, f_{HV} \, f_g \, f_p \, f_{bb} \, f_a \, f_{LU} \, f_{LT} \, f_{RT} \, f_{Lpb} \, f_{Rpb} \qquad \text{(Equation 1)}$$

s = adjusted saturation flow rate (veh/hr/lane)

s_0 = base saturation flow rate (pc/hr/lane)

N = number of lanes

f_w = adjustment factor for lane width

f_{HV} = adjustment factor for heavy vehicles in the traffic stream

f_g = adjustment factor for approach grade

f_p = adjustment factor for existence of a parking lane and parking activity adjacent to lane group

f_{bb} = adjustment factor for blocking effect of local buses that stop within intersection area

f_a = adjustment factor for area type

f_{LU} = adjustment factor for lane utilization

f_{LT} = adjustment factor for left-turn vehicle presence in a lane group

f_{RT} = adjustment factor for right-turn vehicle presence in a lane group

f_{Lpb} = pedestrian adjustment factor for left-turn groups

f_{Rpb} = pedestrian-bicycle adjustment factor for right-turn groups

$$\text{where } f_{HV} = \frac{100}{100 + P_{HV}(E_T - 1)} \qquad \text{(Equation 2)}$$

where f_{LT} = 0.952 for protected left-turns

P_{HV} = percent heavy vehicles in the corresponding movement group (%)

E_T = equivalent number of through cars for each heavy vehicle = PCE = 2.0

A heavy vehicle is not considered a typical vehicle (i.e. passenger car) in terms of design and operation. The HCM accounts for heavy vehicles by applying a heavy vehicle adjustment factor, f_{HV}, to the saturation flow rate equation. It "*accounts for the additional space occupied by heavy vehicles and for the difference in their operating capabilities, compared with passenger cars.*" This factor is determined by applying a passenger car equivalency value, *PCE* (or E_T), to the heavy vehicle as well as a percentage of trucks in the traffic stream. E_T is currently defined as the equivalent number of through cars for each heavy vehicle and is given an assumed value of 2.0. In other words, a lane can accommodate half as many heavy vehicles as it can passenger cars during saturation flow. Although the equivalency is described for through cars, no guidance is provided for what to use for left or right-turns in present or past editions of the HCM. It can only be assumed that the adjustment factor for left or right-turns would accommodate any differences in PCE. Therefore, the only assumption is that a PCE of 2.0 is used for all movements at an intersection.

2.2.3. Measuring Prevailing Saturation Flow Rate

The saturation flow rate for prevailing conditions can also be determined directly by taking measurements in the field. This is the ideal method for determining existing saturation flow rates at the local level if resources are available. It is important to remember the concept of saturation flow when determining the prevailing saturation flow rate. It occurs when the headways of subsequent queue positions converge at a value, the saturation headway. The saturation headway is directly related to the saturation flow rate by the following equation.

$$s = 3600/h \qquad \text{(Equation 3)}$$

s = saturation flow rate (veh/hr/lane)

h = saturation headway (seconds)

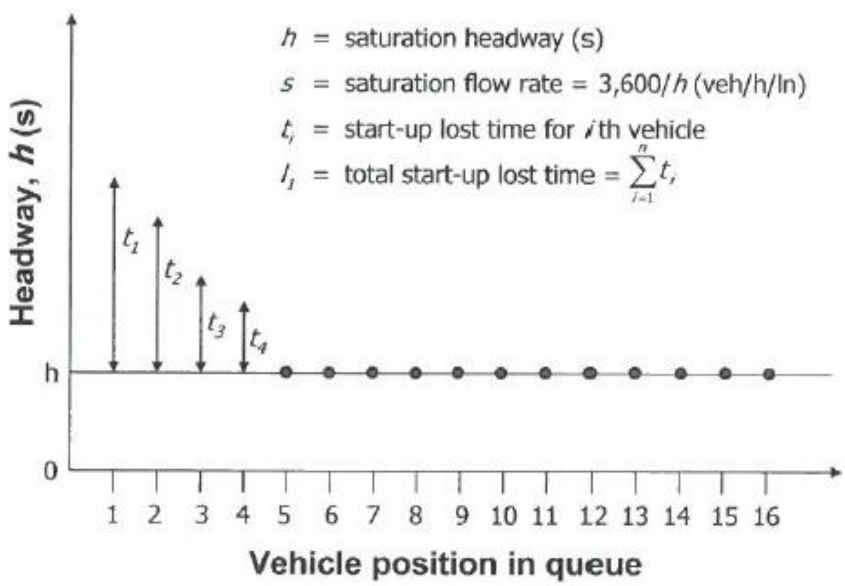

Figure 1. Concept of Headway Convergence from HCM2010 (TRB 2010)

The concept of saturation flow rate and lost time is shown in the figure above, from HCM2010. The headway convergence can be seen in the figure starting with the vehicle in the 5th position.

The prevailing saturation flow rate is calculated by marking the time when the front axle of the 4th vehicle passes the stop line. This is the beginning of saturation flow. The time is also marked when the front axle of the final vehicle that stopped in the queue passes the stop line. This is the end of saturation flow. The difference in time is divided by the number of vehicles in saturation flow, positions 4-n, to determine the saturation headway for the queue. The HCM states that a minimum of 15 signal cycles must be measured to obtain a statistically significant value. The average of saturation headways for each individual cycle is divided into 3600 to determine the prevailing saturation flow rate. It should be noted that the HCM requires the front axle, stop line, and time of 4th queued vehicle as key reference points in the methodology, and they must be maintained for consistency to facilitate information exchange. However, as recent at the 1994 HCM update (TRB 1994), the rear axle was used as the vehicle reference point instead of the front axle. Regardless of the reference points used for obtaining prevailing saturation flow rates, the concept-based saturation flow rate can still be accurately determined if the convergence of saturation headways is obtained.

2.3. Past Research on Saturation Flow Rate and Passenger Car Equivalency Values at Signalized Intersections

Washburn and Cruz-Casas (2010) developed heavy vehicle PCE values for analysis at signalized intersections for through movements only. The observed heavy vehicles were put into one of three different categories – small, medium, and large – and PCE values were given for each category. PCE values were developed based on the relative headway concept, as defined in the most up-to-date HCM at the time, HCM2000. It was not feasible to fulfill the objective of the report using HCM procedures on field data alone, so a custom simulation model was developed for a more robust conclusion. Custom simulation of car-following models was developed so as to provide the user modification of key parameters to best match the field data. The field data from 6 different intersections and a total of 403 queues were used to calibrate the simulation.

Headways were demonstrated to be a function of both the leading and following vehicles pairs. Washburn and Cruz-Casas (2010) defined saturation headway as the average headway of vehicles in positions 5 through 8 of the queue. PCE values of 1.8, 2.2, and 2.8 were ultimately developed for small, medium, and large trucks, respectively. An average PCE value of 2.3 was given if a breakdown of heavy vehicle categories is not available for planners.

Additionally, Washburn and Cruz-Casas (2010) estimated start-up lost time (SLT) due to heavy vehicles in the first four positions of the queue using the percentage of trucks in the traffic stream. They concluded that SLT varies from 2.5 to 17.5 seconds, depending on the percentage and type of trucks in first four queue positions. They also concluded that the HCM recommended base saturation flow rate of 1900 pc/hr/ln appears unattainable over time, as results from the field data showed a corresponding base saturation flow rate of 1773 pc/hr/ln.

Kockelman and Shabih (2000) sought to determine the impacts of light-duty trucks (LDTs) on the capacity of signalized intersections. In the report, LDTs are defined as a class of sport-utility vehicles (SUVs), pickups, and vans with gross vehicle weight ratings below 8500 lbs. This class of vehicle is normally assumed to fall in the passenger car category when calculating saturation flow rates, but they are longer and have lower horsepower-to-curb weight ratios than passenger cars. Given the increasing trends of LDT registrations and the significant percentage of LDTs in the traffic stream, the consideration of the effect on roadway capacity is merited. It was also hypothesized that a passenger car will have a longer headway when following a LDT due to diminished sight distance.

One through movement, left-turn, and right-turn were analyzed. A total of 458 queues were observed. A regression equation was used and built upon headways associated with different types of vehicles, and a weighted least-squares estimation was employed to accommodate heteroscedasticity in the data. Ultimately, PCE values of 1.19, 1.03, and 1.14 were developed for LDTs on through, left-turn, and right-turn traffic, respectively. There is also a breakdown of recommended PCE values for each category of LDT. These values take into consideration the effect that a LDT vehicle has on a passenger car following it. These values are also based against the assumed base saturation flow rate of 1900 pc/ln/hr rather than the report's ideal base saturation flow rate which excludes LDTs. The study also estimated that LDTs contribute about 20% more start-up lost time to the queue than a passenger car.

Tsao and Chu (1995) determined that different adjustment factors should be used for through and left-turning heavy vehicles. The report states that the current HCM practice of calculating saturation flow rates makes two incorrect assumptions: 1.) the left-turn adjustment factor, f_{LT}, is the same for passenger cars and heavy vehicles. 2.) the heavy vehicle adjustment factor, f_{HV}, is the same for through and left-turning vehicles.

A total of 2042 headway measurements were made for through and left-turn movements at two different intersections in Taipei, Taiwan. Headways were taken after the 5^{th} discharged vehicle. Heavy vehicles were defined as any vehicle with more than 4 tires touching the pavement. The results of the study concluded that the effects of the preceding vehicle on the following vehicle's headway were statistically insignificant. Although PCEs were not developed for purposes of the study, the proposed adjustment factors for the saturation flow rate account for the difference in relative headways between passenger cars and heavy vehicles. Tsao and Chu (1995) determined that the left-turn adjustment factor should not be constant under various traffic composition conditions. Ultimately, new adjustment factors were developed for left-turns and heavy vehicles, varying depending on the percentage of heavy vehicles in the traffic stream.

Branston and Van Zuylen (1977) proposed two different methods with multiple linear regression for estimation of saturation flow rate, effective green time, and PCE values. The PCE values were estimated for vans, buses, motorcycles, and heavy vehicles. Through and left-turn movements were included in the analysis for through-car equivalents. Both methods were found to be consistent with each other, though data collection was confined to only a few hours. Start-up lost time was not considered for the analysis, nor was there a recommendation for how to incorporate the results with the HCM procedures.

Sosin (1980) measured the average delay for queues with 100% passenger cars and compared it to delays resulting from different vehicle types present in the queues. With the help of simulation models, delays and PCE values were estimated for intersections located in Poland. This is one of a number of research studies that utilized a form of “delay-based” PCE values.

Molina et al. (1987) presented a frequently referenced delay-based PCE study. PCE values were found for heavy vehicles making through movements at signalized intersections. Heavy vehicles were separated into two different groups: light and heavy trucks. A combination of delay-based PCE values and headway ratios were used to form an equation determining PCE values. Queues with 100% passenger cars were compared to queues with one heavy vehicle, with the increased delay to the vehicles following the heavy vehicle helping to form the basis for the PCE values. The results of the study showed that PCE values varied depending on truck type as well as position in the queue. It also confirmed the belief that different types of heavy vehicles play a significant role in determining the increased delay to queues, and that there is a need to distinguish the different heavy vehicle types when determining capacity. Due to the nature of the methodology, the effect heavy vehicles have on saturation flow rate and start-up lost time was not separated, leading to inordinately high PCE values for early positions in the queue. Because of this, the PCE values found in the study are not compatible for use in HCM equations.

West and Thurgood (1995) expanded upon the findings of Molina et al., and used the same methodology, but for left-turn lanes at compressed diamond interchanges with sharp turning radii. This study acknowledged how the delay-based methodology results in PCE values that conflict with the PCE values as used in the HCM, yielding higher PCE values than other researchers. The results of this study showed that large trucks will increase delays for left-turns with small turning radii compared to movements without this issue, leading to higher PCE values.

Benekohal and Zhao (1996) also developed delay-based PCE values, *D-PCE*. Results showed that PCE values vary according to traffic volume and percentage of heavy vehicles. Results were found using two different categories of heavy vehicles, single unit trucks and combination trucks.

Rahman et al. (2003) determined that PCE values depend on the position of the truck in the queue as well as the percentage of heavy vehicles in the queues. A delay-based method was used for intersections in Japan. Headways were observed to determine base delay and increased delay due to the influence of heavy vehicles in the queue. This study further confirmed that the delay-based method for PCE values varies with queue position of heavy vehicles, with the impact being the greatest if the heavy vehicle is present at the beginning of the queue. Only one category of heavy vehicle was analyzed.

Cuddon and Ogden (1992) examined the influence of different vehicle types on saturation flow rates. Among the results, it was shown that different vehicle type has a great range of performance characteristics. With the HCM providing a single PCE value for all types of heavy vehicles, care should be taken because the proportion of heavy vehicle type has a significant effect on the PCE value.

Ghasemlou et al. (2014) considered different car-following combinations such as H-C, C-H, C-C, and H-H, where C is a passenger car and H is a heavy vehicle. Data from other studies were utilized and the probability of occurrence of each combination was calculated using Bayes' theorem.

Dowling et al. (2014) sought to replace the single PCE value for heavy vehicles at signals with a method that estimates the PCE values at each location. The PCE values are sensitive to the percentage of heavy vehicles as well as the grade of the approach, both of which were found to be significant causes of saturation flow rate adjustment. The results of this study showed that the HCM does not properly account for heavy vehicles when the traffic stream has a significant percentage of heavy trucks, such as 40% or more. Additionally, heavy vehicles on grades, particularly steep grade increases, are also not properly accounted for in the HCM.

Li and Prevedouros (2002) determined that different methods for determining saturation flow rates yield different results. This study analyzed headways and found that the HCM concept of headways convergence after the 4^{th} queued vehicle was difficult to confirm, as headways continued to shorten until the 9^{th}-12^{th} queued vehicle.

Long (2007) also challenged the model of constant saturation flow rate after the 4th queued vehicle. Additionally, the model developed suggests that saturation flow rate is also impacted by downstream cruising speed and the duration of the green phase, two often ignored variables. This author also pointed out how inconsistencies in data collection and reference definitions by researchers lead to ambiguous findings pertaining to saturation flow rates and start-up lost time. The results of this study suggested that the proposed model for estimation of saturation flow rate replace the base saturation flow rate constants in the HCM (HCM has since replaced the base saturation flow rate constant with a default value if no local calibration is available.)

Shao and Liu (2012) suggested that median headways offer a more accurate reflection of the saturation flow rate than mean headways, and that mean headways always skew positively. The results showed that the traditional estimation of saturation headway using mean values leads to unreasonable overestimation of saturation headway.

2.4. Conclusions and Takeaways from Literature Review

Some important takeaways from literature review:

- Historically, research that has been conducted on PCE values often does not take into account different sizes of heavy vehicles. This is largely due to that fact that the HCM only provides a very broad and simple definition of heavy vehicles which only includes one class, any *"vehicle with more than 4 wheels touching the pavement."* As noted by Cuddon and Ogden (1992), the results of such studies are hugely dependent on the local makeup of heavy vehicles. For instance, one would not be able to know if the results are skewed towards small or large trucks. The research presented in the following sections quantifies how big of a difference this can make.

- Research is extremely limited in regards to the differentiation between small, medium, and large trucks. With modern technologies that can provide this type of data, it is important that the state of practice be able to accommodate this data for traffic operations analysis. As previously stated, the HCM only categorizes heavy vehicles into one class or category.
- When developing PCE values, many researchers disregard the role of the PCE value as used by the HCM in computation of saturation flow rate and thus, capacity. Often, researchers combine together the effects heavy vehicles have on start-up lost time and saturation flow rate in the determination of PCE values. This commonly occurs when delay-based ratios are used as the means to develop PCE values. While the researchers make valid conclusions on PCE values, the resulting PCE values are effectively a different interpretation of the PCE value assumed in the HCM for the determination of f_{HV} (i.e. PCE during saturation headway only). The resulting PCE values from these studies should not be used directly with the HCM equation for f_{HV} because the HCM method used to calculate capacity uses start-up lost time and saturation flow rate as separate variables.
- Many researchers conduct studies on PCE, but the results cannot be immediately implemented by traffic engineers because they do not directly tie in with the accepted HCM procedures, and are often presented as a contradiction to current practice.

- Rarely if ever, has research over the past decades attempted to validate the proposed PCE values by comparing the results of the estimated saturation flow rate (using proposed PCE values) to the prevailing saturation flow rate as measured in the field.

At the onset of this study, the main objective was to provide more insight on how different sized vehicles affect the operations at a signalized intersection, specifically with left-turn movements. Moreover, based on the observations from the literature review, it was determined that a research study consistent with theory and concepts in the HCM (TRB 2010) (i.e. saturation headway begins at the convergence of saturation headway) and uses an identical interpretation of PCE (i.e. PCE values are determined during saturation flow only) would be the most beneficial to the traffic engineering community. Additionally, if validation of the results provided acceptable accuracy, the methods of this study may be built upon by others in an attempt to further verify the findings.

3. METHODOLOGY

In an effort to improve understanding of the impact of heavy vehicles at signalized intersections, research was conducted to gain knowledge of the impact of heavy vehicles making protected exclusive left-turn movements at signalized intersections. This impact is represented by the use of a PCE value in the determination of saturation flow rates. By analyzing saturation flow rates as understood in the HCM, and its correlation to headway with various vehicle types, this study concludes the impact of heavy vehicles with field data in a verifiable manner.

3.1. Location of Data Collection

One of the difficulties in studying PCE values of heavy vehicles at signalized intersections is finding locations to gather adequate field data. Typically, locations with high heavy vehicle percentage have low traffic volume. Additionally, to make logical determinations about PCE values, queues with 4 vehicles or less do not provide enough data to measure saturation flow rate, so those queues must be excluded from analysis. Moreover, the HCM suggests a minimum of 9 vehicles in a queue to achieve statistically valid calculations. To complete this study, intersections needed to have long enough queues in order to adequately analyze the impact of heavy vehicles. Because of the difficulty in finding these types of locations, simulations are often used to artificially create longer queues. This research aimed to collect enough data in the field to appropriately and adequately analyze saturation flow rates and PCEs from field data alone.

3.1.1. Intersection Criteria for Adequate Data Collection

- Exclusive left-turn lane
- Protected or protected-permitted left-turn signal phase

- Turn lane with storage length to accommodate at least 9 vehicles in a queue in order to compare results to HCM procedure
- High percentage of heavy vehicles, >15%, especially trucks with trailers (large trucks)
- Protected left-turn signal phase long enough to empty a queue of 9 or more vehicles, including heavy vehicles
- Exclusive left-turn lane storage length as long as possible, so through vehicles could not disrupt the progression

3.1.2. Data Collection Locations

After some preliminary data collection and elimination of intersections that did not fit the above criteria, three approaches were chosen that provided the best opportunity to collect data. It was observed that all three locations had long queues and higher percentages of heavy vehicles due to the proximity of truck stops.

- Site 1 and Site 2 – 2 approaches at 32nd Ave S & 39th St SW
    - Protected-permitted signal phasing
        - Data collected during protected movements only
- Site 3 – 1 approach at 19th Ave S & 45th St S
    - Protected signal phasing
    - Dual left-turn lanes

These intersections were found in Fargo, North Dakota, with a metro area population of 223490 in 2013 (US Census Bureau, Population Division 2014), and it was determined that they would provide the best opportunity for quality data. They all provided exclusive left-turn lanes and long duration protected left-turn phases that could empty long queues with high percentage of heavy vehicles. Incidentally, all three locations were near local truck stops. One intersection, at 32nd Ave S & 39th St SW, provided the most ideal situation, with two approaches fitting the data collection criteria. The westbound left-turn at this location was used to develop the findings of the research. The second approach, southbound left-turn, and a third location, northbound left-turn at 19th Ave S & 45th St S intersection, were used to validate the findings at the first approach.

3.2. Amount of Data Collection

Availability of appropriate intersection conditions limited the number of intersections where sound data could be collected and analyzed. In order to compare the results of this study to HCM, a minimum of 15 queues with queue lengths of at least 9 vehicles would need to be collected. The goal of this study was to collect enough data in the field to appropriately and adequately analyze saturation flow rates and PCE values from field data alone, knowing that it would be difficult to achieve a large number of queues with at least 9 vehicles that could proceed during a protected green phase. At the first approach location (Site 1), 9.75 hours of peak traffic data was collected over the period of five days. 5.0 hours was collected at the second approach (Site 2) location over 3 days, and 9.5 hours was collected at the third approach (Site 3) location over 3 days.

3.3. Time and Season of Data Collection

To collect a representative sample, data was collected during the fall season of 2013, during different peak hour periods of mid-week traffic. The winter season was avoided because of the possible impact of decreased road traction as well as decreased engine performance due to cold weather. The fall season presents the best opportunity to avoid the seasonal discrepancies as well as summer construction. Tuesday, Wednesday, and Thursday traffic also provide consistent work week commutes, which yield the most consistent driver behavior. Lunch-hour and evening peak hours were collected to acquire a varied sample as well as making sure to have long queue lengths.

3.4. Field Data Collection Procedures

In order to determine the PCE values for various vehicle types, headways were measured for each vehicle in the queue, while simultaneously classifying vehicles into 4 different types: passenger cars, small trucks, medium trucks, and large trucks.

3.4.1. Data Collection Devices

This study determines saturation flow rate by the headway of the vehicles in the queues. Headway is best determined by using a time-stamping mechanism as vehicles cross the stop-bar. In order to collect data in a way that limited human error, video was first collected with two camcorders at the intersections from different points of view, and the headway times were measured while reviewing the video footage. The first camcorder was aimed in a manner that a point representing the stop bar could be seen as a vehicle crossed it. However, the angle did not allow the back of the queue to be seen, and it was difficult to tell which vehicles were in the left-turn lane and which vehicles were in the through lanes. The second camcorder was aimed so that the back of the queue could be seen to determine which vehicles actually became part of the queue before the queue was emptied.

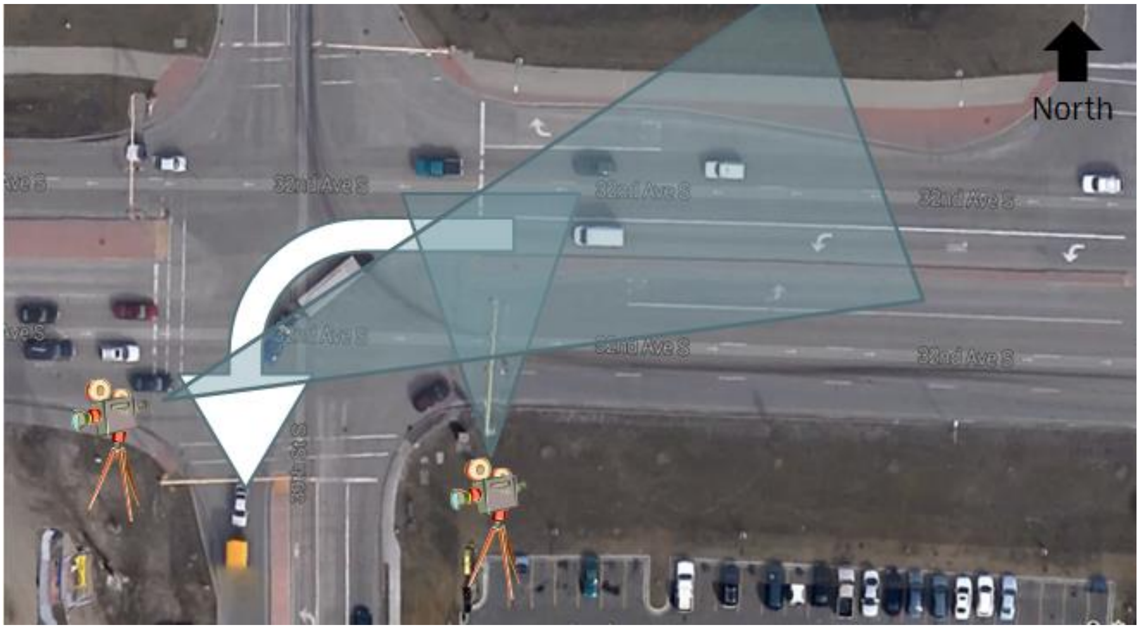

Figure 2. Camcorder Setup and Overview of Site 1: 32nd Ave S & 39th St SW
Courtesy: Google Maps

This allowed the timer to first determine which vehicles were officially part of the queue (any vehicles that came to a complete stop at the back of the queue were included as part of the queue). Both videos were played simultaneously on a computer to review the data.

Figure 3. View from Camcorder 1

Figure 4. View from Camcorder 2

Then, the user could watch the recordings and time-stamp the vehicles with a time-stamping device. Occasionally, an unusual circumstance would disrupt the entire progression of the queue (described in section 3.4.3). The data collected during these occurrences were removed from analysis. Additionally, if any mistakes were made, the queue could be retimed by rewinding the recording back to the start of the queue departure. A traffic data collector by JAMAR technologies was used to measure headways of vehicles in the queue using a time-stamping application. By reviewing the completed time-stamped data, the headway of each vehicle could be reduced and separated based on vehicle type and queue position. 1362 vehicle headways were measured at the first intersection approach for this study.

3.4.2. Vehicle Classification

Vehicles were classified into 4 different categories as shown below. These categories were derived from the categories used by Washburn and Cruz-Casas (2010). Although Washburn and Cruz-Casas did not give a basis for their classification scheme, it was determined that the scheme sufficiently correlated each vehicle category with operational performance for determination of PCE values.

- Passenger Car (PC) – any vehicle with 4 tires on the road, includes cars, SUVs, vans, mini-vans, and all pick-up trucks; motorcycles and bicycles were rare and were excluded from study
- Small Truck (ST) – two-axle trucks, panel trucks, garbage trucks, delivery trucks, passenger cars with trailers, semi-tractor without trailer
- Medium Truck (MT) – three-axle trucks, concrete trucks, large recreational vehicles (RVs), pickup trucks with “5th” wheel trailer
- Large Truck (LT) – trucks with more than 3 axles, semi-tractors with trailers, large buses

The Federal Highway Administration (FHWA) has a 13-category rule or vehicle classification scheme (Hallenbeck et al. 2014). However, this scheme does not directly correlate to operational performance, so it is not an ideal classification scheme for purposes of determining PCE values. Therefore, the previously described categories are used. For informational purposes, Appendix B describes how the 13 class scheme relates to the categories used in this research.

The term “heavy vehicle” is often used interchangeably with the term “truck.” However, note that the truck categories above include passenger cars towing trailers because of their increased length, decreased performance, and negative influence on following passenger cars. Although the categories listed above are not differentiated according to vehicle length, they still reasonably correlate with length-based classification.

Past research (Sosin 1980; Molina et al. 1987; Cuddon and Ogden 1992; West and Thurgood 1995; Benekohal and Zhao 1995; Kockelman and Shabih 2000; Washburn and Cruz-Casas 2010; and Dowling et al. 2014;) has shown that different types of heavy vehicles have varying degrees of effects on the saturation flow rate, and this research aims to associate each type of heavy vehicle with a proper PCE value, as seen in protected exclusive left-turn lanes. Additionally, the decreased performance of passenger cars immediately following each type of heavy vehicle is quantified and added to the PCE value of each respective heavy vehicle type.

One benefit of having intersections near truck stops is the variety of truck types that are witnessed. Trucks that stop at truck stops are often making cross-country or cross-regional deliveries. For this reason, it is believed that the trucks witnessed in this study are a good representation of trucks seen in the Midwestern United States, and possibly the rest of the country.

3.4.3. Direct Measurement of Prevailing Saturation Flow Rates

The HCM provides methods for measuring prevailing saturation flow rates. While these methods were followed to illustrate direct comparisons, many of the conclusions of this study are based on an alternate method that proved to be more effective in analyzing headways. The following paragraphs explain how that decision was made.

It was decided that measuring the headway from first movement, using each vehicles' rear bumper as they crossed the stop-bar provided the most optimal results. Start-up reaction time of 1st vehicle was measured separately and added to the headway of the 1st vehicle in order to determine start-up lost time. Even though the HCM is clear on the methods to determine prevailing saturation flow rates, using this alternate method in this research to determine saturation flow rates is deemed acceptable and verifiable for information exchange because saturation headway will always be achieved eventually regardless of the reference point of measurement on the vehicle. While the HCM provides a best-practice method for determining prevailing saturation headway, it is not guaranteed the technique will produce the converging saturation headway in all cases. It is only estimated that the saturation headway occurs as an average between the 5^{th} and the final vehicle in the queue, and it only measures an average headway for each queue. This technique is used because of the difficulty of finding the converging saturation headway; in order to do so, one must measure the headway of each vehicle in the queue. Finding the converging headway is a time-consuming process and for most purposes, it is typically not practical to differentiate headways for each queue position as well as classifying vehicles into separate categories by vehicle type, as done for the purposes of this research. The saturation headway will eventually begin to converge and it can be determined with adequate data collection regardless of the reference point on the vehicle used. Most current research follows the HCM technique, but without verifying that saturation headway has converged, the findings, although directly comparable to HCM, may be making incorrect assumptions.

This study proposes an alternate method to measure headway with rear bumpers instead of front axles. Using the rear bumper allowed multiple benefits over using the front axle:

- Using front axle effectively measures the headway of the preceding vehicle instead of the input vehicle, which leads to difficult vehicle type classification and data reduction. Using the rear bumper measures the headway of the input vehicle due to its own length and spacing away from the rear bumper of the preceding vehicle.
- Using the rear bumper allows measurement of the headway of the last vehicle in the queue, whereas this vehicle data would be lost using the front axle.

- Using the rear bumper allows measurement of the effect the preceding vehicle can have on the following vehicle, which must be accounted for in determining an accurate PCE. This effect, while inherently measured, would not be able to be separated using front axle.
- By using the rear bumper instead of the rear axle option, one could account for the impact of vehicles with large overhangs past the rear axle, which most heavy vehicles possess.
- Both methods can be used to determine a concept-based converging saturation headway if each position in the queue is analyzed separately.

Only vehicles that were part of a stopped queue were analyzed. The vehicles had to come to a complete stop (if only for the briefest moment) to be considered part of the queue. This follows HCM measurement techniques. Also, if any unusual circumstances affected the queue in an unpredictable manner, the data was discarded. One circumstance was that the queue could not properly discharge from the beginning of the green phase because of vehicles occupying the intersection. Other times, downstream delays affected the discharge of the queue. There were also instances of inattentive drivers that significantly affected the progression.

4. DATA ANALYSIS

Using the methodology described in Chapter 3, the data analysis is provided below. Data was analyzed to determine the concept-based prevailing saturation flow rate. It was compared to the results of HCM techniques for measuring the prevailing saturation flow rate as well as the HCM estimation equation. Additionally, a new revised equation for f_{HV} incorporating proposed PCE values was developed and applied to the researched field conditions. The results of this estimation were also compared to concept-based prevailing saturation flow rate.

4.1. Determination of Prevailing Saturation Flow Rate – HCM Method

The HCM has two methods to determine the saturation flow rate of a lane at a signalized intersection. The first method is to measure the prevailing saturation flow rate in the field with time measurements. The saturation flow rate is calculated by marking the time when the front axle of the 4th vehicle passes the stop line. This is the beginning of saturation flow. The time is also marked when the front axle of the final vehicle that stopped in the queue passes the stop line. This is the end of saturation flow. The difference in time is divided by the number of vehicles in saturation flow to determine the saturation headway for the queue. Each queue must have a minimum of nine vehicles. The HCM states that a minimum of 15 signal cycles must be measured to obtain a statistically significant value. The average of saturation headways for each individual cycle is divided into 3600 to determine the prevailing saturation flow rate.

At the first location approach analyzed, 9.75 hours of data were collected over 5 days at various peak traffic times of the day. In that time, 288 queues were analyzed, and only 25 queues fulfilled the HCM requirement of a minimum of 9 vehicles, representing 8.7% of the queues analyzed. It was observed that the presence of multiple heavy vehicles in the queue made it difficult for 9 vehicles to complete the turn maneuver before the protected green signal ended. The average headway for each of the 25 queues was 2.44 seconds, representing a saturation flow rate of 1475 veh/hr/ln.

4.2. Determination of Concept-Based Prevailing Saturation Flow Rate

The second step in analysis was determining the concept-based prevailing saturation flow rate using individual vehicle headway measurement. This step examines the accuracy of HCM measurement techniques in the situation presented in this study. The "concept-based" prevailing saturation flow rate represents the concept of headway convergence as understood in HCM traffic flow theory described in section 2.2.3, and is the most accurate representation of what might be considered the true saturation flow rate.

4.2.1. Results of Data Collection at Site 1

As explained in the methodology, this study determined the concept-based prevailing saturation flow rate by finding the headway convergence. The figure below shows the average headway for each position in the queue at Site 1: Westbound left-turn movement at the intersection of 32nd Ave S & 39th St SW. There were only 10 queues with 10 vehicles or more, so the data point representing the average headway in the 10th position was removed from the chart. The headway for the 1st position includes the start-up reaction time.

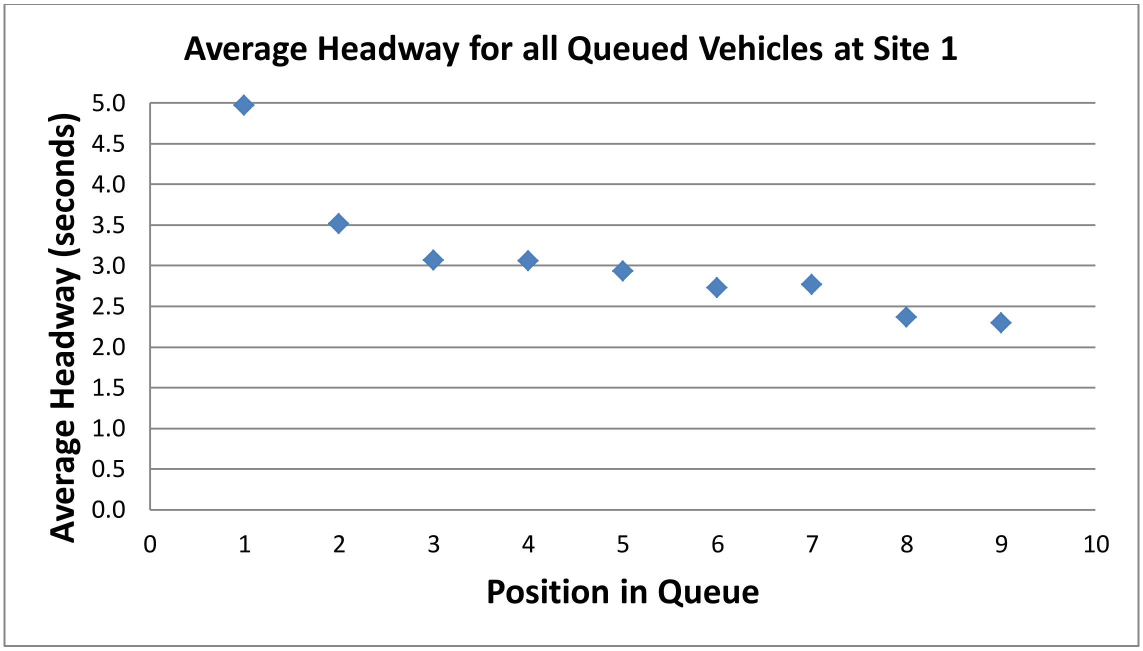

Figure 5. Average Headway for all Queued Vehicles at Site 1

The table below shows the frequency of each vehicle type for each queue position, where *PC* = Passenger Cars, *ST* = Small Truck, *MT* = Medium Truck, and *LT* = Large Truck.

Table 1. Vehicle Type Frequency at Site 1

		Vehicle Type by %				# of Data Points
Position in Queue		*PC*	*ST*	*MT*	*LT*	
	1	63.2%	5.6%	3.1%	28.1%	288
	2	74.7%	5.4%	3.4%	16.5%	261
	3	79.9%	4.1%	1.4%	14.6%	219
	4	72.8%	7.8%	2.8%	16.7%	180
	5	73.5%	7.5%	3.4%	15.6%	147
	6	82.6%	5.5%	2.8%	9.2%	109
	7	75.7%	4.3%	2.9%	17.1%	70
	8	88.4%	9.3%	0.0%	2.3%	43
	9	88.0%	0.0%	4.0%	8.0%	25

The data from the figure and table above led to two conclusions. First, large trucks (LT) were considerably more likely in the 1st queued position. Field observations showed that large trucks found it more difficult to find gaps during the previous signal cycle's permitted movement than other types of vehicles, and thus, they would often wait for the next cycle before making the turn. Second, large trucks were considerably less likely in the 8th queue position or later. A traffic classification count conducted over the same time period showed that the traffic stream consisted of 16.4% large trucks (2.6% medium trucks; 5.7% small trucks) in the lane, so with an adequate sample size, a reasonable expectation would be to have about 16.4% large trucks in each queue position. The small percentage of large trucks in the 8th and later positions is likely a function of decreased performance of large trucks and the duration of the left-turn green signal phase. If a queue had large trucks in it, the protected signal phase would often not be long enough to accommodate more than 7 vehicles. Therefore, the results show that queues of 8 or more vehicles were overrepresented by passenger cars.

4.2.2. Calibration – Bias Introduced by Vehicle Type Percentage

The figure above shows the average headway for all vehicles measured, so any over or under-representation of a certain vehicle type introduces bias into the results. For example, in the table above it can be seen that queue position 6 is overrepresented by passenger cars. Therefore, the average headway measured shows a shorter headway for this position than would be expected had the distribution of vehicle type been consistent for each queue position. Calibration of the data was necessary to remove the bias.

The following figure removes the bias by correlating the mean (average) headway with the expected vehicle type percentages.

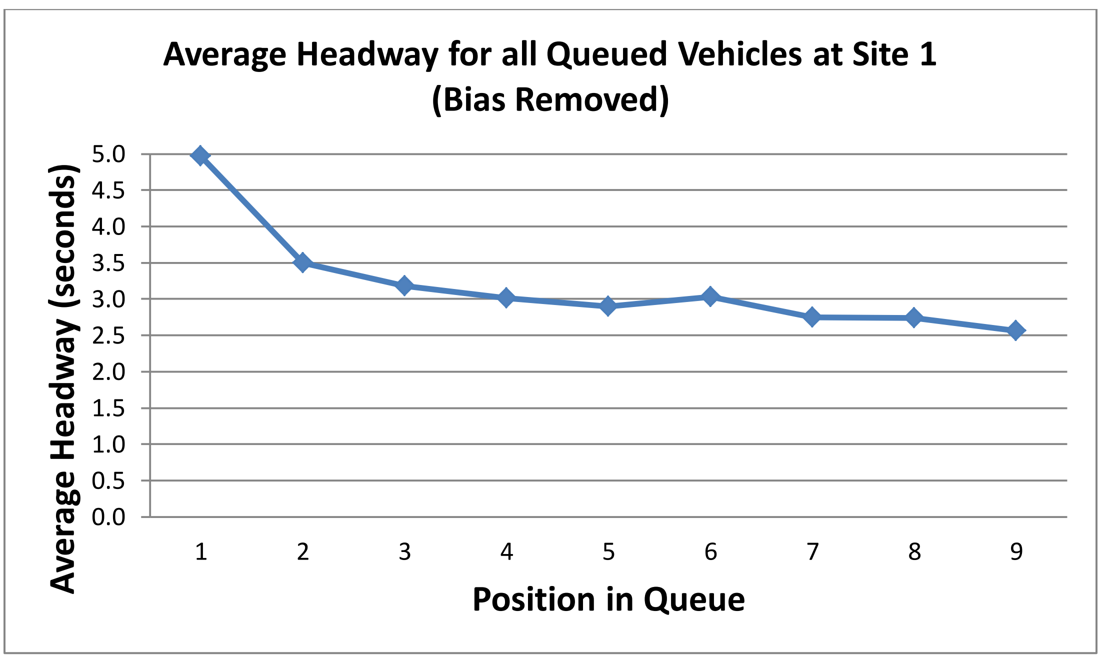

Figure 6. Average Headway for all Queued Vehicles at Site 1 (Bias Removed)

The 6th – nth queue positions were combined into one data group to give better statistical relevance by vehicle type. As can be seen in the figure below, the headways from Site 1 begins to converge at the 5th queued vehicle, which correlates with the assumption made by the HCM. Although the average headway of vehicles in position 5 (2.89 seconds) is higher than the 6+ position (2.86 seconds), it is well documented that true (concept-based) convergence point is difficult to pinpoint with field measurements. The HCM method of averaging the headways between the 4th – nth vehicle effectively removes this known variation. In fact, this is illustrated in the figure above, in which the average headway (bias removed) in the 6th position (3.03 seconds) alone was *higher* than the 5th position, which furthered the validation for choosing the 5th position as the beginning of convergence.

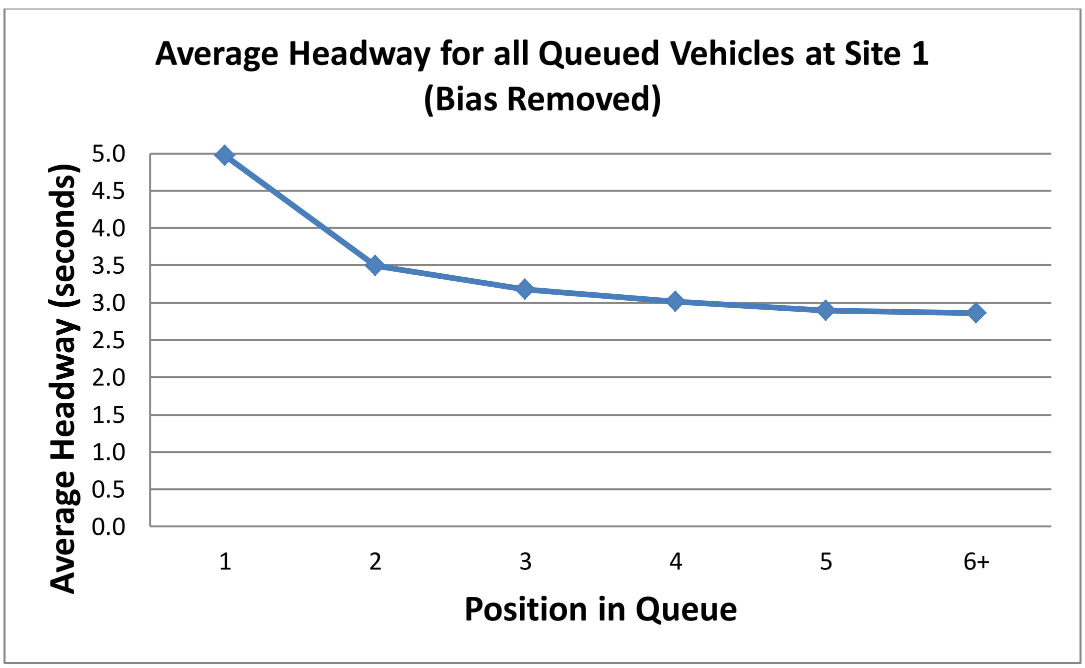

Figure 7. Average Headway for all Queued Vehicles at Site 1
Note: Queue positions 6 and later were combined into one point.

4.2.3. Determination of Saturation Headway using Field-Collected Data

A few different methods were considered in the determination of saturation headway from the data collected. The first option that was eliminated was using the method recommended by the HCM or a variation where a queue must have a minimum number of vehicles. This study has already explained why this method is problematic for protected left-turn movements with high percentage of heavy vehicles. While this method has value, it presents an arduous task to deduce the impact of different vehicles types and remove the bias introduced in data collection.

The second option that was eliminated was computing the average headway for each queue position individually 5^{th}, 6^{th},….nth, then averaging the results. While this method could remove the bias, it gave too much weight to queue positions with lower statistical confidence, such as the 9^{th} position, where it is extremely difficult to acquire headway data with heavy vehicles making protected exclusive left-turn movement. For example, if the average headway for vehicles in the 5^{th} and 9^{th} positions had equal weight in the computation, one would be giving data with high statistical confidence (5^{th} position) equal weight to data with lower statistical confidence (9^{th} position). There is simply less data for the 9^{th} position. Field observations showed that unless there was substantial amount of data collection and a green phase of sufficient duration, data for the 9^{th} queue position was always underrepresented by heavy vehicles.

The third option that was eliminated was simply accepting the results of the 5^{th} position as the convergence headway, but this places too much weight on one queue position. The data acquired from the 6^{th} and later positions should not be discounted.

It was essential to remove the bias from the data that was introduced by the randomness of vehicle type experienced. It was decided that averaging headways by vehicle type for all of the vehicles in the 5^{th} –nth position was the optimum method to compute the saturation headway, and then to remove the bias for vehicle percentage. There were multiple reasons why averaging the headways of all vehicles in the 5th – nth position was chosen as the best option:

- Statistical confidence was strengthened because of increased number of data points.
- The computation gave more weight to earlier queue positions, which by nature are more common (see final column in Table 1).
- Eliminated the green phase duration as a variable, which allows for better information exchange and comparison with other sites.

The results of the chosen method found the saturation headway to be 2.87 seconds, leading to a concept-based saturation flow rate of 1254 veh/hr/ln. Recall that the saturation flow rate using the HCM method was 1475 veh/hr/ln. This shows a substantial overestimation of saturation flow rate by 17.6% using the HCM method of measurement.

The figure below shows the true (concept-based) convergence of saturation headway and the HCM determined saturation headway.

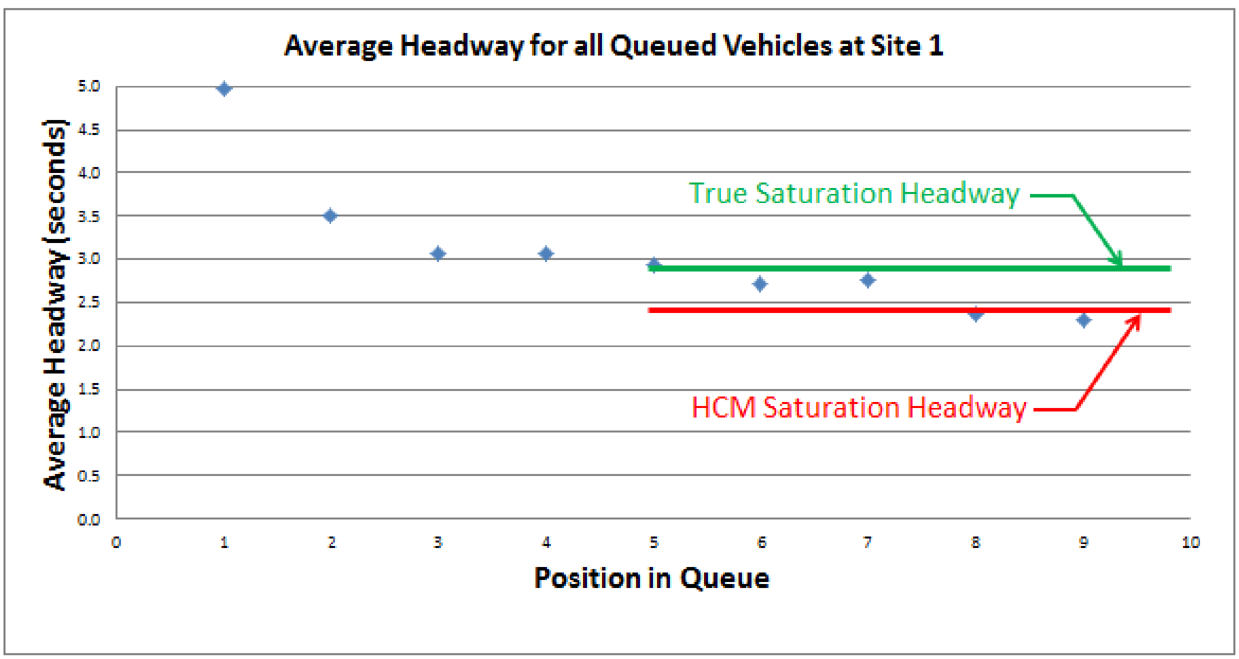

Figure 8. Average Headway for all Queued Vehicles at Site 1 – Comparison of Saturation Headway

4.3. Estimation of Saturation Flow Rate – HCM Method

The third step in analysis was determining how accurate the HCM estimates saturation flow rates using the saturation flow rate equation and adjustment factors.

Recall that the HCM equation estimates the saturation flow rate with a number of adjustment factors and a default base saturation flow rate which is based on population. Since the Fargo metropolitan area is less than 250000 people, the default base saturation flow rate is 1750 pc/hr/ln.

$$S = S_0 \, N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \qquad \text{(Equation 1)}$$

s_0 = 1750 pc/hr/ln

N = 1

f_w = 1

f_{HV} = 0.802

f_g = 1.01

f_p = 1

f_{bb} = 1

f_a = 1

f_{LU} = 1

f_{LT} = 0.952

f_{RT} = 1

f_{Lpb} = 1

f_{Rpb} = 1

$$\text{where } f_{HV} = \frac{100}{100+P_{HV}(E_T-1)} = \frac{100}{100+24.7(2.0-1)} = 0.802 \qquad \text{(Equation 2)}$$

where $f_g = 1 - \frac{P_g}{200} = 1 - \frac{-2.0}{200} = 1.01$ (Equation 4)

where f_{LT} = 0.952 for protected left-turns

$S = S_0 N f_{HV} f_g f_{LT}$ = 1349 veh/hr/ln

With all the variables determined, the equation yields a result of 1349 veh/hr/ln. This estimation yields a saturation flow rate that is substantially higher than reality (7.6% error), though closer than the HCM field-measurement technique.

4.4. Determination of PCE Values Based on Field Data

The fourth step in analysis was determining PCE values for small, medium, and large trucks and incorporating these PCE values into a revised equation for f_{HV}.

This study hypothesizes that a better understanding of PCE values and an alternate equation for the adjustment factor, $f_{HV,}$ incorporating small, medium, and large trucks will lead to a more accurate estimation of saturation flow rates using the equation by the HCM. First the saturation headway of passenger cars only, H_{pc}, was determined. Then, the saturation headway of small, medium, and large trucks, H_i, was determined. Lastly, the additional mean headway of the passenger car immediately following type *i* trucks, ΔH_i, was determined. This additional headway was assumed to apply to all vehicle types. The relative headway ratio method shown below (derived from Greenshields et al. 1947 and Molina et al. 1987) was used to determine the PCE values for each heavy vehicle type, *i*.

$PCE_i = (H_i + \Delta H_i)/H_{PC}$ (Equation 5)

The figure below shows the converging headway of all vehicle types, *i*. All queue positions after the 5th position were combined into one 6+ position to show that at the 5th and later queue positions, the headway converges. Note that the convergence of passenger cars was determined by using passenger car headways that could not be influenced by heavy vehicles at any point prior in the queue. This clearly showed a convergence at the 5th position as it was nearly identical to the average headways of vehicles in the 6th and later position (both 2.09 seconds).

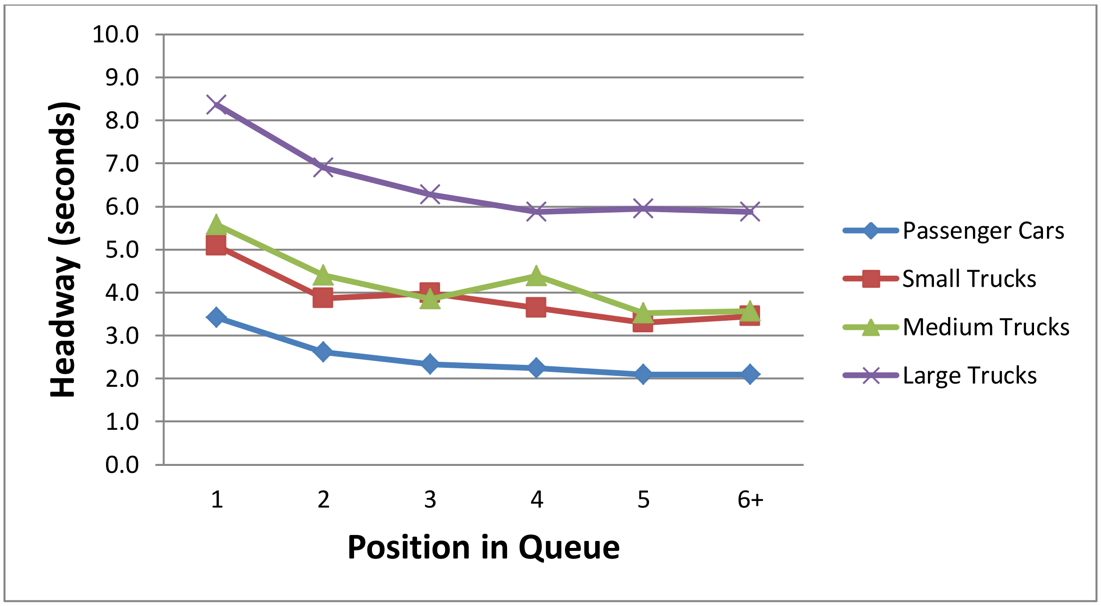

Figure 9. Average Headway for Queued Vehicles by Vehicle Type, *i*, at Site 1
Note: Passenger car data series was not influenced by prior heavy vehicles in the queue.

The figure below shows the headway of passenger cars following different vehicle types. Again, the points converge at the 5th and later positions. Note that because of the relatively small percentage of small and medium trucks in the traffic stream, the data does not converge as nicely for these vehicle types. The table below shows the numerical headway values determined.

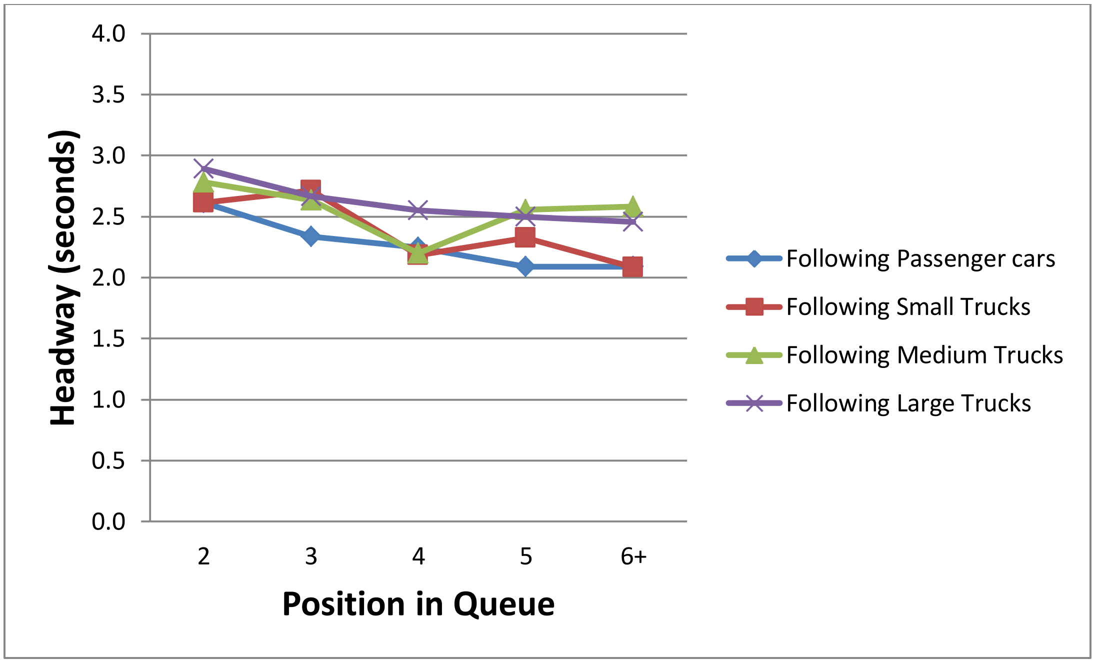

Figure 10. Average Passenger Car Headway for Queued Vehicles following Vehicle Type, *i*, at Site 1

Table 2. Saturation Headway + Impact on following Passenger Cars

	Passenger Cars	Small Trucks	Medium Trucks	Large Trucks
Saturation Headway, H_i	2.09	3.38	3.55	5.91
Passenger Car Headway following Vehicle Type, *i*	2.09	2.18	2.57	2.47
Additional Headway of passenger car, ΔH_i	0	0.09	0.48	0.38
Saturation Headway + Additional Headway = $H_i + \Delta H_i$	$\boldsymbol{H_{PC}}$ **= 2.09**	**3.47**	**4.03**	**6.29**

The PCE findings using headway ratio (equation 5) are shown below:

PCE of small truck = PCE_{ST} = 3.47/2.09 = 1.66

PCE of medium truck = PCE_{MT} = 4.03/2.09 = 1.93

PCE of large truck = PCE_{LT} = 6.29/2.09 = 3.01

The proposed equation for f_{HV} to incorporate PCE values for small, medium, and large trucks making left-turns is shown with the following equation:

$$f_{HV} = \frac{100}{100 + \%HV_{thru}(PCE_{thru} - 1) + \%ST_{left}(PCE_{ST} - 1) + \%MT_{left}(PCE_{MT} - 1) + \%LT_{left}(PCE_{LT} - 1)}$$

(Equation 6)

The skeleton of the original f_{HV} equation remains intact with $\%HV_{thru}$ and PCE_{thru} replacing the original variables P_{HV} and E_T, respectively. In an exclusive left-turn lane, these variables would be equal to zero. Note that there are no variables for right-turning vehicles in the equation above. Providing PCE values and variables for right-turns is outside the scope of this research study, as well as PCE values for different types of heavy vehicles for through (thru) movements. However, they can be easily added to the equation in a similar manner that left-turns are shown, should they be developed in the future.

4.5. Estimation of Saturation Flow Rate – Proposed Revised Equation

The fifth step in analysis was determining saturation flow rate at Site 1 using the saturation flow rate equation incorporating a revised equation for f_{HV}.

$$f_{HV} = \frac{100}{100 + 0\%(PCE_{thru} - 1) + 5.7\%(1.66 - 1) + 2.6\%(1.93 - 1) + 16.4\%(3.01 - 1)}$$

$$f_{HV} = \frac{100}{100 + 0 + 3.762 + 2.418 + 32.964}$$

$$f_{HV} = 0.719$$

To check the accuracy of the revised adjustment factor equation, the variables witnessed at the site are entered into the equation, with a yielded result of $f_{HV} = 0.719$

Note that the percentage entries for this equation were acquired from all vehicles that used the left-turn lane, including vehicles that were not part of queues and those that came through on a permitted movement.

The base saturation flow rate can be determined by using the saturation headway of passenger cars, $H_{PC} =$ 2.09, and other known adjustment factors at Site 1. The base saturation flow rate is calculated as follows, derived from equations 1 and 3:

$$S_0 = 3600/H_{PC} /f_g/f_{LT} \qquad \text{(Equation 7)}$$

$$S_0 = 3600/2.09/1.01/0.952 = 1791 \text{ pc/hr/ln}$$

Using S_0 and f_{HV}, the revised estimation for saturation flow rate is calculated by using equation 1 as follows:

$$S = S_0\, N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} = S_0 f_{HV} f_g f_{LT} \qquad \text{(Equation 1)}$$

$$S = (1791)(1)(0.719)(1.01)(0.952) = 1238 \text{ veh/hr/ln}$$

Recall that the concept-based saturation flow rate was calculated to be 1254 veh/hr/ln. The result shows an acceptably close estimation (1.3% error), and much more accurate than HCM methods. This estimation was determined by using the proposed PCE values and the percentage of each vehicle type witnessed in the lane, including vehicles that were not part of queues and those that came through on a permitted movement. It was determined independently of the concept-based field-measured saturation flow rate.

4.6. Saturation Flow Rate – Comparison of Results

The sixth step in analysis was a comparison of results. For fair comparison, estimated saturation flow rate using HCM method is also shown using now-determined base saturation flow rate of 1791 pc/hr/ln.

- Prevailing saturation flow rate – Concept-Based = 1254 veh/hr/ln
- Prevailing saturation flow rate – HCM Method = 1475 veh/hr/ln (17.6% error)
- Estimated saturation flow rate – HCM Method (where S_0 = 1750 pc/hr/ln) = 1349 veh/hr/ln (7.6% error)
- Estimated saturation flow rate – HCM Method (where S_0 = 1791 pc/hr/ln) = 1381 veh/hr/ln (10.1% error)
- Estimated saturation flow rate – Proposed Method = 1238 veh/hr/ln (1.3% error)

Interestingly, the HCM method for determining prevailing saturation flow rate in the field was far less accurate than the estimation equation. Also, using the now-determined base saturation flow rate actually increased the error for HCM estimation.

4.7. Validation of Findings

The seventh step was a validation with Sites 2 and 3. Field data were collected at two additional sites to test the validation of the proposed PCE values. Using the same method as previously described, headway data was collected for the southbound left-turn at the intersection 32^{nd} Ave S & 39^{th} St SW (Site 2). The data set at this location was not as robust as the first location. Because of this, the results shown in the figures below are not as consistent as the results from Site 1.

4.7.1. Validation at Site 2: Southbound Left-Turn at 32nd Ave S & 39 St SW

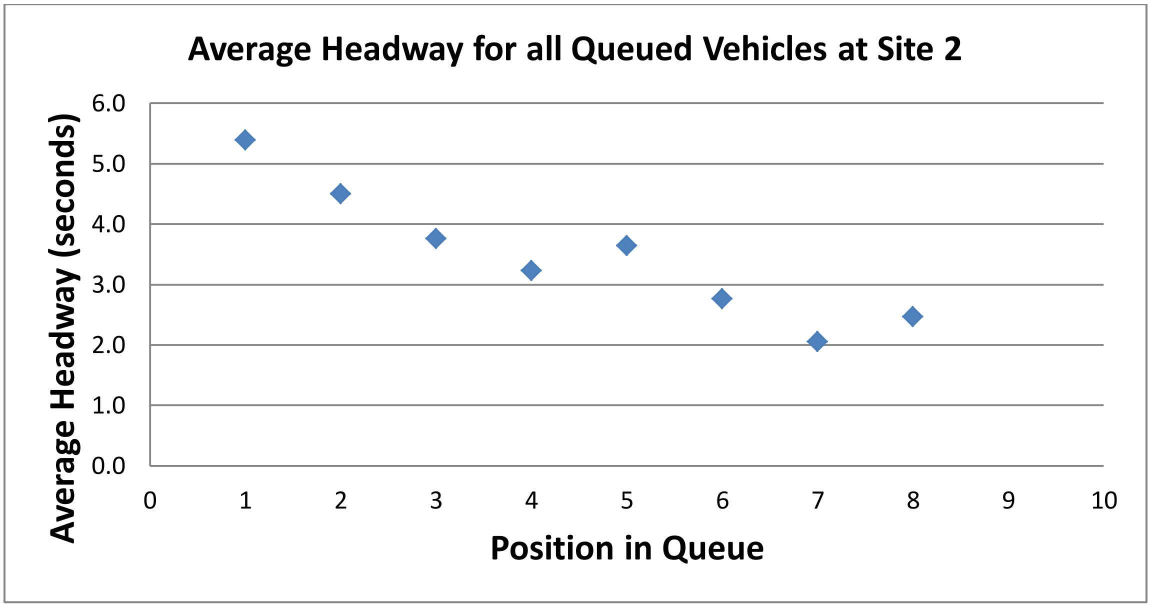

Figure 11. Average Headway for all Queued Vehicles at Site 2

The majority of queues (84%) were 4 vehicles or less, with the distribution shown in the table below. As previously described, to determine the convergence headway, the bias was removed by correlating the average headways for each queue position with the true vehicle type percentage (66.2% passenger cars, 2.9% small trucks, 3.2% medium trucks, and 27.7% large trucks), with the exception of the 1st queue position.

Some of the vehicle types did not occur in certain queue positions, such as large trucks in queue position 7. In these instances, the average headway was artificially replaced with aggregated results. For example, the average headway for large trucks in the 6+ positions was 6.364 seconds, so this was the average headway used for large trucks in queue position 7 for Site 2. In some cases the lack of data was more pronounced, so some results were artificially replaced with results from Site 1. For example, the average headway for small trucks could not be determined for positions 6, 7, 8, and 9 because there were none, so 3.450 seconds was used for each of these positions, because that was the average headway for queue positions 6+ at Site 1.

Table 3. Vehicle Type Frequency at Site 2

		Vehicle Type by %				# of Data Points
Position in Queue		*PC*	*ST*	*MT*	*LT*	
	1	58.2%	1.3%	3.2%	37.3%	158
	2	62.2%	5.9%	2.5%	29.4%	119
	3	65.9%	4.5%	5.7%	23.9%	88
	4	80.3%	1.5%	1.5%	16.7%	66
	5	65.4%	3.8%	3.8%	26.9%	26
	6	92.3%	0.0%	0.0%	7.7%	13
	7	100%	0.0%	0.0%	0.0%	6
	8	100%	0.0%	0.0%	0.0%	3
	9	0.0%	0.0%	0.0%	100%	1

After the bias was removed (figure shown below), it was confirmed that the convergence headway was met in the 5th position of the queue.

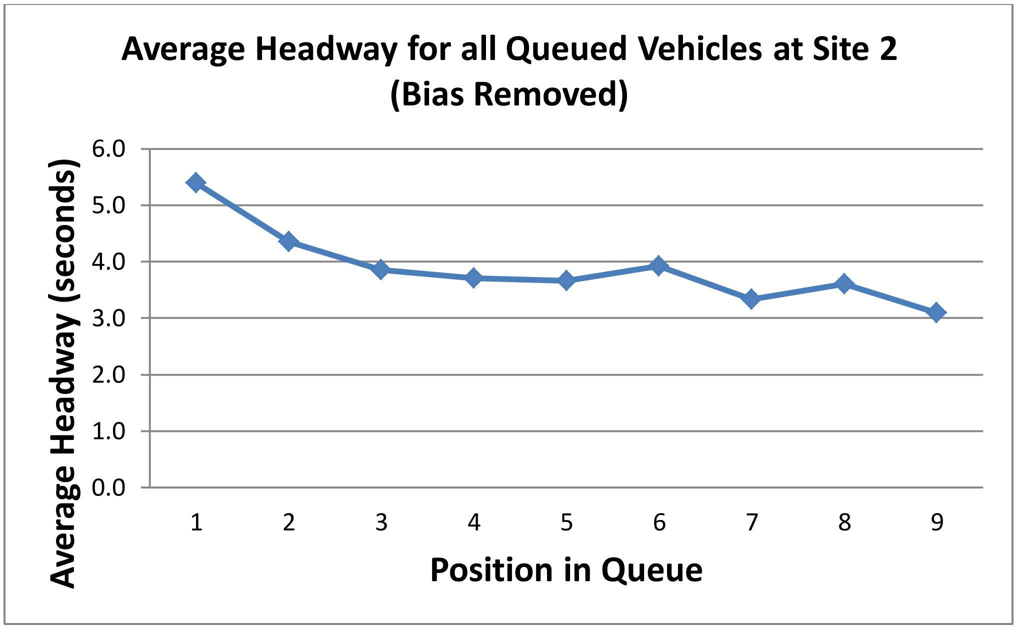

Figure 12. Average Headway for all Queued Vehicles at Site 2 (Bias Removed)

Using the same procedure shown for Site 1, averaging headways of all of the vehicles in the 5^{th} – nth position and removing the bias for vehicle percentage, the saturation headway was found to be 3.58 seconds, leading to a concept-based saturation flow rate of 1006 veh/hr/ln.

The next step in the validation is to apply the revised estimation equation for saturation flow rate.

Passenger cars = 66.2%

Small trucks = 2.9%

Medium trucks = 3.2%

Large trucks = 27.7%

$$f_{HV} = \frac{100}{100 + \%HV_{thru}(PCE_{thru} - 1) + \ \%ST_{left}(PCE_{ST} - 1) + \%MT_{left}(PCE_{MT} - 1) + \%LT_{left}(PCE_{LT} - 1)}$$

(Equation 6)

$$f_{HV} = \frac{100}{100 + 0(PCE_{thru} - 1) + 2.9\%(1.66 - 1) + 3.2\%(1.93 - 1) + 27.7\%(3.01 - 1)}$$

$$f_{HV} = \frac{100}{100 + 0 + 1.914 + 2.976 + 55.677}$$

$$f_{HV} = 0.623$$

Using the same procedure as Site 1, convergence headway for passenger cars only at this location was found to be 2.31 seconds, so the base saturation flow is computed below, derived from equations 1 and 3:

$$S_0 = 3600/H_{PC} /f_g/f_{LT} \qquad \text{(Equation 7)}$$

$$S_0 = 3600/2.31/0.99/0.952 = 1654 \text{ pc/hr/ln.}$$

Using S_0 and f_{HV} the revised estimation for saturation flow rate is calculated by using equation 1 as follows:

$$S = S_0\, N f_W f_{HV} f_g\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{LT}\, f_{RT}\, f_{Lpb}\, f_{Rpb} = S_0 f_{HV} f_g f_{LT} \qquad \text{(Equation 1)}$$

$$S = (1654)(1)(0.623)(0.99)(0.952) = 971 \text{ veh/hr/ln}$$

Recall that the concept-based prevailing saturation flow rate was determined to be 1006 veh/hr/ln, so this validation example shows an error of about 3.5%. While the error is reasonably close, it is believed that a better sample size used to determine H_{PC} would have led to a more accurate estimation. The sample size was only 12 points, and it is believed that two of the points, while not statistical outliers, led to an overly high average. If one of the two large headways was removed, it would lead to H_{PC} of 2.22 seconds, and thus S_0 would equal 1721 veh/hr/ln, and S

would equal 1011 veh/hr/ln, which would be an error of only 0.5%. Regardless, it appears that the revised equation for f_{HV} is validated at Site 2 with minimal error.

To compare how the HCM estimation performs, the computation is shown below.

$$S = S_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} = S_0 f_{HV} f_g f_{LT} \qquad \text{(Equation 1)}$$

Where s_0 = 1654 pc/hr/ln

$$f_{HV} = \frac{100}{100+P_{HV}(E_T-1)} = \frac{100}{100+33.8(2.0-1)} = 0.747 \qquad \text{(Equation 2)}$$

$$f_g = 1 - \frac{P_g}{200} = 1 - \frac{2.0}{200} = 0.99 \qquad \text{(Equation 4)}$$

where f_{LT} = 0.952 for protected left-turns

$S = S_0 f_{HV} f_g f_{LT}$ = 1164 veh/hr/ln

So therefore, the HCM estimation yields 15.7% error at Site 2.

4.7.2. Validation at Site 3: Northbound Left-Turn at 45th St S & 19th Ave S

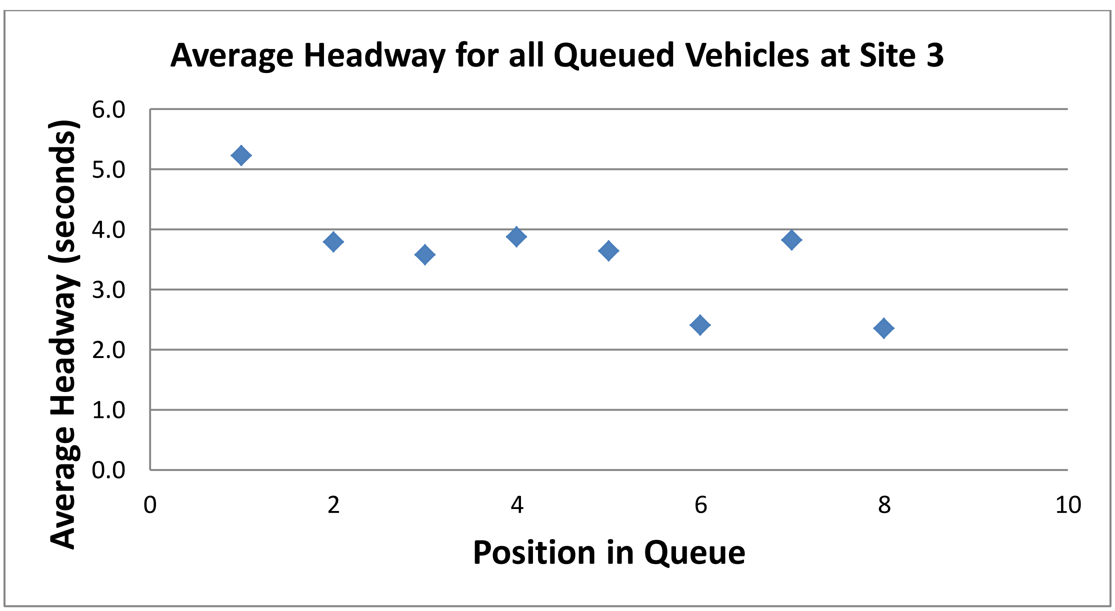

Figure 13. Average Headway for all Queued Vehicles at Site 3

At Site 3 there were dual left-turn lanes. Measurements were taken at both the inside and the outside left-turn lanes. However, nearly all of the heavy vehicles used the outside left-turn lane (lane farthest to the right). Therefore, the results from the inside lane are not included in the analysis.

The majority of queues (77%) were 4 vehicles or less, with the distribution shown in the table below. To determine the convergence headway, the bias was removed by correlating the average headways for each queue position with the true vehicle type percentage (69.1% passenger cars, 2.5% small trucks, 1.2% medium trucks, and 27.2% large trucks), with the exception of the 1st queue position.

Similarly to Site 2, some of the vehicle types did not occur in certain queue positions, such as large trucks in queue position 8. In these instances, the average headway was artificially replaced with aggregated results. For example, the average headway for large trucks in the 6+ positions was 6.554 seconds, so this was the average headway used for large trucks in queue position 8 for Site 3. In some cases the lack of data was more pronounced, so some results were artificially replaced with results from Site 1. For example, the average headway for small trucks could not be determined for positions 6, 7, 8, and 9 because there were none, so 3.450 seconds was used for each of these positions, because that was the average headway for 6+ positions at Site 1.

Table 4. Vehicle Type Frequency at Site 3

		Vehicle Type by %				# of Data Points
Position in Queue		*PC*	*ST*	*MT*	*LT*	
	1	65.7%	1.9%	1.9%	30.6%	265
	2	71.2%	2.7%	1.4%	24.7%	219
	3	72.8%	2.6%	0.0%	24.5%	151
	4	62.0%	1.0%	3.0%	34.0%	100
	5	65.0%	3.3%	1.7%	30.0%	60
	6	93.3%	0.0%	0.0%	6.7%	30
	7	63.6%	0.0%	0.0%	36.4%	11
	8	100%	0.0%	0.0%	0.0%	3
	9	100%	0.0%	0.0%	0.0%	1

Although the large truck percentage in queue position 1 was greater than the overall average, the results were not as pronounced as at Sites 1 and 2. It is believed that this is because there was not permitted signal phase at Site 3.

After the bias was removed (figure shown below), it was confirmed that the convergence headway was met in the 5th position of the queue.

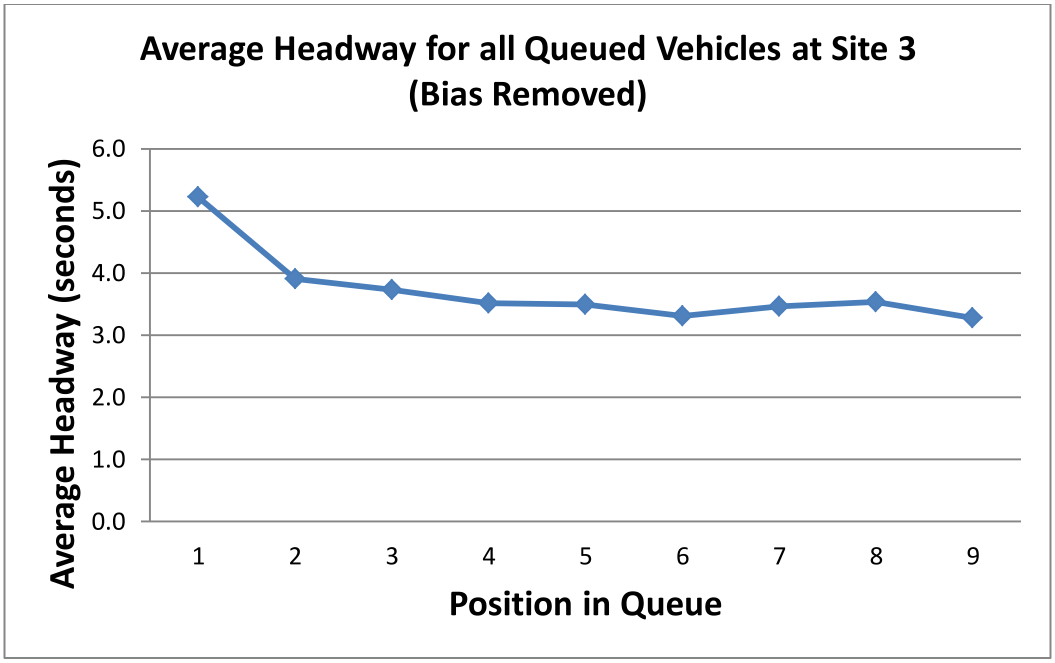

Figure 14. Average Headway for all Queued Vehicles at Site 3 (Bias Removed)

Using the same procedure shown for Sites 1 and 2, averaging headways of all of the vehicles in the 5^{th} – nth position and later and removing the bias for vehicle percentage, the saturation headway was found to be 3.41 seconds, leading to a concept-based saturation flow rate of 1056 veh/hr/ln.

The next step in the validation is to apply the revised estimation equation for saturation flow rate.

Passenger cars = 69.1%

Small trucks = 2.5%

Medium trucks = 1.2%

Large trucks = 27.2%

$$f_{HV} = \frac{100}{100 + \%HV_{thru}(PCE_{thru} - 1) + \%ST_{left}(PCE_{ST} - 1) + \%MT_{left}(PCE_{MT} - 1) + \%LT_{left}(PCE_{LT} - 1)}$$

(Equation 6)

$$f_{HV} = \frac{100}{100 + 0(PCE_{thru} - 1) + 2.5\%(1.66 - 1) + 1.2\%(1.93 - 1) + 27.2\%(3.01 - 1)}$$

$$f_{HV} = \frac{100}{100 + 0 + 1.650 + 1.116 + 54.672}$$

$$f_{HV} = 0.635$$

Using the same procedure shown for Sites 1 and 2, convergence headway for passenger cars only at this location was found to be 2.10 seconds, so the base saturation flow is computed below, derived from equations 1 and 3:

$$S_0 = 3600/H_{PC} /f_g/f_{LT} \quad \text{(Equation 7)}$$

$$S_0 = 3600/2.10/1.0/0.952 = 1801 \text{ pc/hr/ln}$$

Using S_0 and f_{HV} the revised estimation for saturation flow rate is calculated by using equation 1 as follows:

$$S = S_0\, N f_W f_{HV} f_g\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{LT}\, f_{RT}\, f_{Lpb}\, f_{Rpb} = S_0\, f_{HV} f_g f_{LT} \quad \text{(Equation 1)}$$

$$S = (1801)(1)(0.635)(1.0)(0.952) = 1089 \text{ veh/hr/ln}$$

Recall that the concept-based prevailing saturation flow rate was determined to be 1056 veh/hr/ln, so this validation example shows an error of about 3.1%. Therefore, it appears that the revised equation for f_{HV} is validated at Site 3.

To compare how the HCM estimation performs, the computation is shown below.

$$S = S_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} = S_0 f_{HV} f_g f_{LT} \quad \text{(Equation 1)}$$

Where s_0 = 1801 pc/hr/ln

$$f_{HV} = \frac{100}{100+P_{HV}(E_T-1)} = \frac{100}{100+30.9(2.0-1)} = 0.764 \quad \text{(Equation 2)}$$

$$f_g = 1 - \frac{P_g}{200} = 1 - \frac{0.0}{200} = 1.00 \quad \text{(Equation 4)}$$

where f_{LT} = 0.952 for protected left-turns

$S = S_0 f_{HV} f_g f_{LT}$ = 1310 veh/hr/ln

So therefore, the HCM estimation yields 24.1% error at this Site 3.

5. DISCUSSION OF RESULTS

The body of knowledge on the parameter of saturation flow rate and the consensus thereof is contained in the HCM. While it presents the standard practice for traffic practitioners, it is a living document that adapts to findings of new and improved research. Recent research has raised concerns that the HCM is underestimating the impact of heavy vehicles on saturation flow rate. This study aimed to explore further the research of heavy vehicles by determining PCE values for protected exclusive left-turn movements at signalized intersections.

This study served two purposes: 1.) to investigate the adequacy of HCM methods used to determine saturation flow rate for protected exclusive left-turn movements with heavy vehicles, and 2.) To provide improved PCE values for heavy vehicles derived from field-data alone. The underlying premise was that improved estimation of the heavy vehicle adjustment factor would lead to more accurate estimations of saturation flow rates, particularly when heavy vehicles represent a high percentage of the traffic stream. Improved estimations of saturation flow rate would ultimately lead to improved geometric design and signal plans, thus decreasing delays and improving LOS.

Although the methods and procedures provided in the HCM are accepted as the standard practice in determination of saturation flow rate, this study shows that the accuracy of these methods are not as effective in the specific, but not uncommon situation in which a large percentage of heavy vehicles are making protected exclusive left-turn movements. The results of this study illustrate that methods presented in the HCM can show improved accuracy with subtle changes such as revising the equation for f_{HV} and providing PCE values for different types of heavy vehicles. Ultimately, improved methods for operations and capacity analysis are the goal, providing traffic practitioners the necessary data to make proper engineering judgment regarding intersection geometry and signal plan designs.

Some limitations of the HCM method for measuring prevailing saturation flow rate in the field are listed below:

- Each queue must have a minimum of nine vehicles in the queue, which is a scenario that is difficult to find in the field for exclusive left-turn lanes and a high percentage of heavy vehicles.
- Protected green phase for left-turn movements is typically set for 15-30 seconds, which may not be enough time to accommodate nine vehicles when there are a high percentage of heavy vehicles in the lane.

By using the HCM procedure to measure prevailing saturation flow rate at Sites 1,2 and 3, only the queues with an inordinately high percentage of passenger cars qualified for analysis (i.e. minimum of 9 vehicles), which leads to the belief of a saturation flow rate that is higher than in reality. In order to verify the concept-based prevailing saturation flow rate, it was necessary to undertake more detailed data collection in the field than is practical or recommended in the current standard practice.

When a large percentage of heavy vehicles are represented in the traffic stream, the duration of the green signal phase presents a significant challenge in achieving a "one-size fits all" method in measuring prevailing saturation flow rates. The *Canadian Capacity Guide for Signalized Intersections* (Teply et al. 2008) provides an alternative to measuring prevailing saturation flow rates in which as little as 10-20 seconds of saturated departures may be used to determine saturation flow rate. Though the results are not directly compatible with the HCM, an approximate regression relationship is provided. Further investigation is required in this area and is recommended for future research.

The HCM method for estimating saturation flow rate is commonly used as standard practice, but the results of this study provide changes needed for improvement of HCM methods. The comparison of results for all methods showed a substantial improvement in accuracy at the three sites by using the proposed methods. PCE values were determined based on relative headway ratios at Site 1 and later validated based on application of proposed PCE values at Sites 2 and 3. These values, when used in conjunction with the revised equation for f_{HV}, can be used in the future for more accurate determination of saturation flow rates for protected exclusive left-turn movements.

It is believed that the observed field conditions offered a good representation of heavy vehicles in the US. With the sites' proximity to truck stops, the representation of heavy vehicles in the study included a variety of trucks that move freight across the US instead of being tied to specific truck types moving the same type of payload.

This report provides recommended PCE values for small, medium, and large trucks. While modern data collection technology has the ability to provide this breakdown to traffic engineering practitioners, standard practice still accepts a consolidation of all heavy vehicles into one group. How should a traffic engineer use the results of this study if distribution of different sizes of heavy vehicle is unknown? One option is to average the three PCE values and input this number into the original HCM equation for f_{HV}, but engineering judgment should take precedence. While this study found that the vast majority of heavy vehicles fell in the large truck category, this will not always be and may rarely be the case. All sites used in this study were in vicinity of truck stops, which likely led to an overrepresentation of the large truck compared to small and medium trucks. Other sites may have a much different distribution.

6. CONCLUSIONS AND RECOMMENDATIONS

The HCM is the primary guide used by traffic engineering researchers and practitioners for geometric and operational design of signalized intersections. It provides methods to account for the impact that heavy vehicles have on saturation flow rate. However, a literature review indicated that the impact of heavy vehicles at signalized intersections is being underestimated, leading to an overestimation of capacity. This study's objective was to better understand how heavy vehicles impact the operations of exclusive left-turn movements at signalized intersections, while incorporating the findings to improve HCM procedures for determination of saturation flow rate for protected exclusive left-turn movements at signalized intersections.

One of the difficulties in this type of research is finding ideal field conditions for the study. A local search of the region was conducted in order to find the most ideal conditions for data collections, so that valid results could be found based on field data alone. Site 1 presented the most ideal conditions, so the PCE values recommended in this study are based on the data from Site 1. Sufficient data samples were collected at this location to find the concept-based saturation flow rate and also to develop PCE values for three different types of heavy vehicles based on relative headway ratios. With a thorough understanding of the concept of saturation flow rate as understood by the HCM, and how it can be found in the field, this study developed PCE values of 1.66, 1.93, and 3.01 for small, medium, and large trucks, respectively, and validated the results at Site 2 and Site 3. The largest error experienced was 3.5% for the proposed methods. Comparatively, the HCM current practice methods yielded a range of errors of 10.1% - 24.1% at the same locations.

The PCE values were determined using a relative headway ratio of passenger cars and three different types of heavy vehicles. The impact that heavy vehicles have on immediately following vehicles were also incorporated into the results. The resulting PCE values were added to a revised equation for f_{HV}, which is an adjustment factor used by the HCM to determine an estimated saturation flow rate. The concept-based saturation flow rate was determined at three different sites and compared to the results of the revised equation to determine error.

Some conclusions that were made based on the results of this study:

- Because of availability of better data collection technology that can classify heavy vehicles into more than one group, the HCM needs to accommodate more heavy vehicle types in determination of the adjustment factor, f_{HV}.
- The HCM method for measuring prevailing saturation flow rate in the field is not as effective for protected exclusive left-turn movements with a high percentage of heavy vehicles, producing an error of 17.6% at one site. Furthermore, the procedure could not be administered at the other two sites because only one queue at each of those locations met the procedure requirements of a minimum of nine queued vehicles (2 out of 423 queues during peak traffic periods).
- The HCM method for estimating saturation flow rates for protected exclusive left-turn movements at signalized intersections likely underestimates the impact of heavy vehicles by using a default PCE value of 2.0 if large trucks are present.
- Large trucks present the most problematic vehicle classification for geometric and operational design of signalized intersections, because the results of this study show a PCE value of 3.01, which is more than 50% higher than the current default PCE value for heavy vehicles of 2.0 in the HCM.
- The revised equation for f_{HV} in this study, incorporating the proposed PCE values for small, medium, and large trucks provided a substantially improved estimation of

saturation flow rates at all three sites studied, and is recommended for use for protected exclusive left-turn movements at signalized intersections where the distribution of passenger cars, small trucks, medium trucks, and large trucks is known.

It is believed that the results and recommendations of this study should be used if a transportation practitioner encounters a protected exclusive left-turn movement at signalized intersections with large trucks, because the impact of large trucks on saturation flow rate is being substantially underestimated by the current HCM PCE value of 2.0 for heavy vehicles. If there are a high percentage of small and/or medium trucks, the current HCM method actually provides a conservative estimate of saturation flow rate, because the results of this study found the PCE value of small and medium trucks to be less than 2.0.

Other observations and findings:

- Saturation flow rate was confirmed to occur with the 5^{th} – nth queued positions, regardless of vehicle type.
- All heavy vehicles negatively impacted the operations of passenger cars in the queue position immediately after the heavy vehicle.
- The method to measure headways using the rear bumper of each vehicle was found to be more appropriate for research of this type.
- Heavy vehicles are more likely to occur in the 1^{st} position of the queue, particularly if the signal phasing is protected-permitted
- Start-up lost time was found to be 3.17 seconds, 2.97 seconds, and 2.74 seconds for Sites 1, 2, and 3, respectively. There did not appear to be a correlation of start-up lost times with percentage of heavy vehicles; Site 1 had 24.7% heavy vehicles, Site 2 had

33.8% heavy vehicles, and Site 3 had 30.9% heavy vehicles. It seems more likely that the start-up lost time increases as large trucks become more overrepresented in the 1^{st} queued position; Site 1 had 71.3% more large trucks in the 1^{st} queue position than other positions; Site 2 had 34.7% more large trucks in the 1^{st} queue position than other positions; Site 3 had 12.5% more large trucks in the 1^{st} queue position than other positions.

- Base Saturation flow rate was different at all three sites; Site 1 was 1791 pc/hr/ln, Site 2 was 1654 pc/hr/ln, Site 3 was 1801 pc/hr/ln. This provides further evidence that there are more factors affecting saturation flow rates than are accounted for with adjustment factors at this time.
- The HCM default base saturation flow rate does not work well for a metropolitan area similar to Fargo, North Dakota. The population of the area is very close the default saturation flow rate threshold of 250000 people. One would not expect the driver behavior to significantly change once the population hits the threshold.
- Of passenger car vehicle type, Site 1 was 65.1% LDT, Site 2 was 60.1% LDT, and Site 3 was 59.4% LDT.
- It did not appear that percentage of heavy vehicles influenced the PCE values. However it is believed that the percentage of heavy vehicles influences start-up lost time, though perhaps not in the way that most researchers have concluded. As percentage of heavy vehicles increase, saturation headway increases. Since saturation headway affects the calculation of start-up lost time, start-up lost time cannot simply be determined by comparing headways of queues with heavy vehicles against headways of queues with no heavy vehicles.

- HCM needs to better specify what the PCE value represents when used for calculation of f_{HV} at signalized intersections. The PCE is an input for calculation of saturation flow rate. Therefore, studies that determine PCE values as part of the research should not recommend the results for use in the equation f_{HV} as used by HCM unless those results were derived from measurements taken during saturation flow rate conditions, i.e. after the saturation head way has converged or after the first 4 vehicles as specified by HCM.
- Headway data collection at signalized intersections for determination of saturation flow rate is a time-consuming process. Refining data collection technologies for this purpose would greatly aid the capabilities of these types of studies and advance the understanding of departure headways at signalized intersections.

6.1.1. Recommendations for Future Work

- Determine a recommendation for default base saturation flow rate, S_0, for a metropolitan area of 200000 – 300000 population.
- Determine PCE values for different sizes of heavy vehicles for exclusive right-turn lanes.
- Determine a standard procedure to differentiate between small, medium, and large sized trucks
- Measuring prevailing saturation flow rates in the field for protected exclusive left-turn movements needs to be improved upon. The current HCM method is inadequate in this situation, but the varying length of green signal phases presents a significant challenge in determining a better method.

- Quantitatively determine the extent that improvements in the calculation of f_{HV} will have on delay and LOS.
- Utilize emerging data collection technologies to aid in the process of collecting departure headways at signalized intersections and investigate whether the future of "connected vehicles" will play a part in data collection for saturation flow rate studies or similar topics.

REFERENCES

Benekohal, R. F. and Zhao, W. (1996) "Effects of heavy vehicles on intersection delay and passenger car equivalents." *Moving Forward in a Scaled-Back World, ITE International Conference Proceedings*, Dana Point, California, March.

Branston, D,. and Van Zuylen, H. (1978). "The estimation of saturation flow, effective green time and passenger car equivalents at traffic signals by multiple linear regression." *Transportation Research, Part A*, 12(1), pp. 47-53.

Clayton, A.J.H. (1941). "Road Traffic Calculations." *Journal of the Institution of Civil Engineers*, No. 7, June, pp. 247-264.

Cuddon, A. P. and K. W. Ogden (1992). "The Effects of Heavy Vehicles on Saturation Flows at Signalised Intersections," *Proceedings of 16TH ARRB Conference,* Vol. 16, Part 5, Perth, Western Australia, pp. 1-18.

Dowling, R., List, G., Yang, B., Witzke, E. and Flannery, A. (2014). "*NCFRP Report 31: Incorporating Truck Analysis into the Highway Capacity Manuals*." Transportation Research Board, Kittelson & Associates, Inc., Oakland, CA

Ghasemlou, K., Topal, A., Tanyel, S., Aydin, M.M. and Kazemi, A.A. (2014). "Investigation the Effect of Heavy Vehicles on Capacity of Signalized Intersections Based on Bayes' Theorem" *Proceedings of the Second Congress of the Transportation and Development Institute of ASCE*, Orlando, Florida, June 8-11, 2014, CDROM.

Greenshields, B.D., Schapiro, D., and Ericksen, E.L. (1947). *Traffic performance at urban street intersections.* Technical Report No. 1. Yale Bureau of Highway Traffic, Whaples-Bullis Co., New Haven, CT.

Hallenbeck, M.E., Selezneva, O.I., and Quinley, R. (2014). "Verification, refinement, and applicability of long-term pavement performance vehicle classification rules." *Publication No. FHWA-HRT-13-091*, <http://www.fhwa.dot.gov > (May 21, 2016).

Highway Research Board (1965). *Highway capacity manual*. Special Report 87. National Research Council, Washington, D.C.

Kockelman, K.M., and Shabih, R.A. (2000). "Effect of Light-Duty Trucks on the Capacity of Signalized Intersections." *Journal of Transportation Engineering*, 126(6), pp. 506-512.

Minge, E. (2010). *Evaluation of non-intrusive technologies for traffic detection.* Minnesota Department of Transportation, SRF Consulting Group, Inc., Minneapolis, MN

Li, H. and Prevedouros, P.D. (2002). "Detailed Observations of Saturation Headways and Start-up Lost Times," *Transportation Research Record*, No. 1802, pp. 44-53.

Long, G. (2007). "Driver Behavior Model of Saturation Flow." *Transportation Research Record*, no. 2027, pp. 65-72.

Miller, A.J. (1968). "Australian road capacity guide: provisional introduction and signalized intersections." *Australian Road Research Board,* Bulletin No. 4.

Molina, C.J., Messer, C.J., and Fambro, D.B. (1987). *Development of Passenger Car Equivalencies for Large Trucks at Signalized Intersection.* Research Report FHWA/TX-87/397-2, Texas Transportation Institute, College Station, Texas.

Rahman, M., Okura, I. and Nakamura, F. (2003). "Measuring Passenger Car Equivalent (PCE) for Large Vehicles at Signalized Intersections." *Journal of the Eastern Asia Society for Transportation Studies,* Vol. 5, Yokohama, Japan.

Shao, C. and Liu, X. (2012). "Estimation of Saturation Flow Rates at Signalized Intersections." *Discrete Dynamics in Nature and Society*, Volume 2012, Hindawi Publishing Corporation, 9 pages.

Sofokidis, H., Tilles, D.L., and Geiger, D.R. (1973). "Evaluation of intersection-delay measurement techniques." *Highway Research Record* 453, Washington, D.C., pp. 28-47

Sosin, J. A. (1980). "Delays at Intersections Controlled by Fixed-Cycle Traffic Signals", *Traffic Engineering and Control*, Vol. 21 (8/9), pp. 407-413.

Stokes, R.W. (1988). "Comparison of Saturation Flow Rates at Signalized Intersections" *ITE Journal*, November 58(11), pp. 15-20.

Strong, D.W. (1994). "1994 Changes to chapter 9 of the 1985 highway capacity manual (signalized intersections)." *Proc., Compendium of Technical Papers, 64th ITE Annual Meeting, ITE, Dallas, TX., 160-164.*

Teply, S., Allingham, D.E., Richardson, D.B., and Stepherson, B.W. (2008). *Canadian capacity guide for signalized intersection,* 3rd Ed., Institute of Transportation Engineers, District 7, Canada.

Transportation Research Board (1985). *Highway capacity manual*. Special Report 209. National Research Council, Washington, D.C.

Transportation Research Board (1994). *Highway capacity manual*. Special Report 209. National Research Council, Washington, D.C.

Transportation Research Board (2000). *Highway capacity manual*. National Research Council, Washington, D.C.

Transportation Research Board (2010). *Highway capacity manual*. National Research Council, Washington, D.C.

Tsao, S. and Chu, S. (1995). "Adjustment Factors for Heavy Vehicles at Signalized Intersections." *Journal of Transportation Engineering,* 121(2), 150-157.

US Census Bureau, Population Division. *Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2013.* Release Date: March 2014. <www.factfinder.census.gov/>

Washburn, S.S., and Cruz-Casas, C. O. (2010). “Impact of Trucks on Signalized Intersection Capacity.” *Computer-Aided Civil and Infrastructure Engineering*, 25(6), 452-467.

Webster, F.V. (1958). *Traffic signal settings.* Road Research Technical Paper No. 39. Road Research Laboratory, London. Her Majesty’s Stationary Office, London.

West, J.E. and Thurgood, G.S. (1995). “Developing Passenger-Car Equivalents for Left-Turning Trucks at Compressed Diamond Interchanges.” *Transportation Research Record*, no. 1484, pp. 90-97.

Zegeer, J.D., Vandehey, M., Blogg, M., Nguyen, K., and Ereti, M. (2008). *NCHRP Report 599: Default values for highway capacity and level of service analyses.* Transportation Research Board, Kittelson & Associates, Inc., Fort Lauderdale, FL

APPENDIX A. DATA TABLES

A.1. Site 1 Summary Tables

The following tables, A1-A5, show a summary of the data collected at Site 1.

Table A1. Site 1 – Number of Queues

Site 1 - Number of Queues									
Queue Length (veh)	1	2	3	4	5	6	7	8	9+
# queues	27	42	39	33	38	39	27	18	25

Table A2. Site 1 – Number of Headways Collected

Site 1 - Number of Headways Collected									
Queue Position	1	2	3	4	5	6	7	8	9
# of data	288	261	219	180	147	109	70	43	25

Table A3. Site 1 – Mean Headway (seconds) – PC only

Site 1 - Mean Headway (seconds) - PC only		
	PC (no trucks prior)	
Queue Position	mean	# of data
1	3.41	182
2	2.61	122
3	2.34	78
4	2.24	49
5	2.09	34
5+	**2.09**	76
6+	2.09	42

Table A4. Site 1 – Mean Headway (seconds) by Queue Position and Vehicle Type, *i*

Site 1 - Mean Headway (seconds) by Queue Position and Vehicle Type, i								
	PC		ST		MT		LT	
Queue Position	mean	# of data	mean	# of data	mean	# of data	mean	# of data
1	3.41	182	5.08	16	5.58	9	8.37	81
2	2.70	195	3.86	14	4.41	9	6.90	43
3	2.42	175	3.98	9	3.84	3	6.28	32
4	2.30	131	3.65	14	4.39	5	5.87	30
5	2.19	108	3.29	11	3.29	5	5.94	22
6	2.22	90	3.45	6	3.80	3	6.48	10
7	2.07	53	2.75	3	3.76	2	5.68	12
8	2.14	38	3.87	4	-	0	4.95	1
9	2.06	22	-	0	3.29	1	4.45	2
5+	2.15	325	**3.38**	25	**3.55**	12	**5.91**	47
6+	2.13	217	3.45	14	3.57	7	5.87	25

Table A5. Site 1 – Mean Headway (seconds) – PC's Following Different Vehicle Types, *i*

Site 1 - Mean Headway (seconds) for PC's Following Different Vehicle Types, i								
	PC following PC		PC following ST		PC following MT		PC following LT	
Queue Position	mean	# of data	mean	# of data	mean	# of data	mean	# of data
1	-	0	-	0	-	0	-	0
2	2.61	122	2.61	10	2.78	9	2.89	52
3	2.34	78	2.72	10	2.63	4	2.67	27
4	2.24	49	2.18	3	2.20	3	2.55	19
5	2.09	34	2.33	9	2.55	4	2.50	16
5+	**2.09**	76	**2.18**	22	**2.57**	8	**2.47**	42
6+	2.09	42	2.09	13	2.58	4	2.46	26

A.2. Site 2 Summary Tables

The following tables, A6-A9, show a summary of the data collected at Site 2.

Table A6. Site 2 – Number of Queues

Site 2 - Number of Queues									
Queue Length (veh)	1	2	3	4	5	6	7	8	9+
# queues	39	31	22	40	13	7	3	2	1

Table A7. Site 2 – Number of Headways Collected

Site 2 - Number of Headways Collected									
Queue Position	1	2	3	4	5	6	7	8	9
# of data	158	119	88	66	26	13	6	3	1

Table A8. Site 2 – Mean Headway (seconds) – PC only

Site 2 - Mean Headway (seconds) - PC only		
	PC (no trucks prior)	
Queue Position	mean	# of data
1	3.41	92
2	2.69	40
3	2.45	24
4	2.34	15
5	2.39	7
5+	2.31	12
6+	2.21	5

Table A9. Site 2 – Mean Headway (seconds) by Queue Position and Vehicle Type, *i*

Site 2 - Mean Headway (seconds) by Queue Position and Vehicle Type, i								
	PC		ST		MT		LT	
Queue Position	mean	# of data	mean	# of data	mean	# of data	mean	# of data
1	3.41	92	4.41	2	5.19	5	8.52	59
2	2.86	74	5.29	7	4.60	3	7.80	35
3	2.56	58	3.43	4	5.03	5	6.84	21
4	2.54	53	4.04	1	5.96	1	6.21	11
5	2.38	17	2.98	1	4.35	1	6.69	7
6	2.34	12	-	0	-	0	7.77	1
7	2.05	6	-	0	-	0	-	0
8	2.47	3	-	0	-	0	-	0
9	-	0	-	0	-	0	4.96	1
5+	2.33	38	2.98*	1	4.35**	1	6.62	9
6+	2.28	21	-	0			6.36	2

* Mean headway from Site 1 (3.38 seconds) used for calibration because of lack of data.

** Mean headway from Site 1 (3.55 seconds) used for calibration because of lack of data.

A.3. Site 3 Summary Tables

The following tables, A10-A13, show a summary of the data collected at Site 3.

Table A10. Site 3 – Number of Queues

Site 3 - Number of Queues									
Queue Length (veh)	1	2	3	4	5	6	7	8	9+
# queues	46	68	51	40	30	19	8	2	1

Table A11. Site 3 – Number of Headways Collected

Site 3 - Number of Headways Collected									
Queue Position	1	2	3	4	5	6	7	8	9
# of data	265	219	151	100	60	30	11	3	1

Table A12. Site 3 – Mean Headway (seconds) – PC only

Site 3 - Mean Headway (seconds) - PC only		
	PC (no trucks prior)	
Queue Position	mean	# of data
1	3.53	174
2	2.38	107
3	2.31	60
4	2.14	27
5	2.14	15
5+	2.10	32
6+	2.06	17

Table A13. Site 3 – Mean Headways (seconds) by Queue Position and Vehicle Type, *i*

Site 3 - Mean Headway (seconds) by Queue Position and Vehicle Type, i								
	PC		ST		MT		LT	
Queue Position	mean	# of data	mean	# of data	mean	# of data	mean	# of data
1	3.53	174	4.72	5	5.72	5	8.85	81
2	2.48	156	3.53	6	4.83	3	7.55	54
3	2.42	110	4.20	4	-	0	6.95	37
4	2.24	62	2.92	1	5.70	3	6.71	34
5	2.25	39	4.95	2	4.94	1	6.44	18
6	2.12	28	-	0	-	0	6.28	2
7	2.18	7	-	0	-	0	6.69	4
8	2.36	3	-	0	-	0	-	0
9	1.98	1	-	0	-	0	-	0
5+	2.20	78	4.95*	2	4.94**	1	6.47	24
6+	2.15	39	-	0	-	0	6.55	6

* Mean headway from Site 1 (3.38 seconds) used for calibration because of lack of data.

** Mean headway from Site 1 (3.55 seconds) used for calibration because of lack of data.

APPENDIX B. VEHICLE TYPE (HEAVY VEHICLE CLASSIFICATION)

Figure B1. Examples of Small Trucks
Note: Two-axle trucks, panel trucks, garbage trucks, delivery trucks, passenger cars with trailers, semi-tractor without trailer

Figure B2. Examples of Medium Trucks
Note: Three-axle trucks, concrete trucks, large recreational vehicles (RVs), pickup trucks with "5th" wheel trailer

Figure B3. Examples of Large Trucks
Note: Trucks with more than 3 axles, semi-tractors with trailers, large buses

Table B1. FHWA Vehicle Classification Scheme

Class 1	Motorcycles
Class 2	Passenger Cars
Class 3	Other Two-Axle Four-Tire Single Unit Vehicles
Class 4	Buses
Class 5	Two-Axle, Six-Tire, Single-Unit Trucks
Class 6	Three-Axle Single Unit Trucks
Class 7	Four or More Axle Single-Unit Trucks
Class 8	Four or Fewer Axle Single Trailer Trucks
Class 9	Five-Axle Single-Trailer Trucks
Class 10	Six or More Axle Single-Trailer Trucks
Class 11	Five or Fewer Axle Multi-Trailer Trucks
Class 12	Six-Axle Multi-Trailer Trucks
Class 13	Seven or More Axle Multi-Trailer Trucks

Table B2. FHWA Vehicle Classification Scheme Relation to Research Scheme

Class	Typical Category	With Trailer	With 5th Wheel	Exceptions
Class 1	-	-	-	
Class 2	PC	ST	-	
Class 3	PC	ST	MT	All pickup trucks are PC
Class 4	LT	LT	-	Small bus is ST (2-axle) or MT (3-axle)
Class 5	ST	MT or LT	-	If trailer, then 3-axle is MT and 4-axle is LT
Class 6	MT	LT	-	Garbage Truck is ST; Semi-tractor without trailer is ST
Class 7	LT	-	-	Concrete Truck is MT
Class 8	LT	-	-	3-axle is MT; 4-axle is LT
Class 9	LT	-	-	
Class 10	LT	-	-	
Class 11	LT	-	-	
Class 12	LT	-	-	
Class 13	LT	-	-	