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Assessing Passenger Car Equivalency Factors for High Truck Percentages

Jianan Zhou
Graduate Research Assistant
Department of Civil Engineering
University of Nebraska-Lincoln

Laurence Rilett, Ph.D., PE
Distinguished Professor

Elizabeth Jones, Ph.D.
Associate Professor

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Nebraska Transportation Center
262 Prem S. Paul Research Center at Whittier School
2200 Vine Street
Lincoln, NE 68583-0851
(402) 472-0141

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Jianan Zhou
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Associate Professor
Department of Civil Engineering
University of Nebraska-Lincoln

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16. Abstract

The Passenger Car Equivalent (PCE) values in the Highway Capacity Manual (HCM) 2010 might not be valid for western Nebraska freeway conditions. This is because: 1) Interstate 80 (I-80) experiences high truck percentages (25% to 60%), while the HCM provides PCE values up to 25% of the truck percentage; 2) the average speed of trucks are observed lower than passenger cars, which is incompatible with the HCM assumption that the free speed of all vehicle types is the same at level terrain; and 3) it is unclear whether the “average” truck used in the simulation study for PCE values in the HCM is representative of a typical Nebraska truck. Also, a platoon may form when a truck passes another, resulting in a delay for vehicles that are following, who may wish to be traveling at a faster speed. The objective of this research is to estimate and recommend PCEs for basic freeway segments on I-80 with a high truck percentage in western Nebraska. This research study will examine aspects of the current HCM PCE determination methodology to see if it is representative of Nebraska’s traffic on basic freeway segments. To accomplish these tasks, field data was collected using ITS data collection equipment, including video and radar detectors. This data will be used to: 1) analyze characteristics of platoons on I-80; 2) calibrate a VISSIM 5.4 traffic simulation model that can be used to estimate PCE values in a manner similar to that used to calculate the HCM values; and 3) calculate PCEs using a variety of approaches (e.g., headway-based method and delay-based method). The PCE values under truck restriction conditions are also calculated using these simulation data. The results suggest the PCEs in the HCM 2010 for level freeway segments (1.5) may not be suitable for traffic flow on I-80 in western Nebraska. The PCEs based on the equal-density method (HCM method) using the different speed distributions for trucks and passenger cars with an average of 3.0, and the PCEs based on the delay method with an average of 2.8, are finallyrecommended.

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Abstract

The Passenger Car Equivalents (PCE) values in Highway Capacity Manual (HCM) 2010 might not be valid for western Nebraska freeway conditions. This is because 1) the Interstate 80 (I-80) experiences high truck percentage (25% to 60%), while the HCM provides PCE up to 25% truck percentage; 2) the average speed of trucks are observed lower than passenger cars, which is incompatible with the HCM assumption that the free speed of all vehicle types is the same at level terrain; and 3) it is unclear whether the "average" truck used in the simulation study for PCE values in HCM is representative of a typical Nebraska truck. Also, a platoon may form when a truck passes another, resulting in a delay for vehicles that are following, who may wish to be traveling at a faster speed. The objective of this research is to estimate and recommend PCEs for basic freeway segments on I-80 with high truck percentage in western Nebraska. This research study will examine aspects of the current HCM PCE determination methodology to see if it is representative of Nebraska's traffic on basic freeway segments. To accomplish these tasks, field data was collected using ITS data collection equipment, including video and radar detectors. This data will be used to: 1) analyze characteristics of platoons on I-80; 2) calibrate a VISSIM 5.4 traffic simulation model that can be used to estimate PCE values in a manner similar to that used to calculate the HCM values; and 3) calculate PCEs using a variety of approaches (e.g. headway-based method and delay-based method). The PCE values under truck restriction conditions are also calculated using these simulation data. The results suggest the PCEs in the HCM 2010 for level freeway segments (1.5) may not be suitable for traffic flow on I-80 in western Nebraska. The

PCEs based on equal-density method (HCM method) using the different speed distributions for trucks and passenger cars with an average of 3.0, and the PCEs based on delay method with an average of 2.8, are finally recommended.

Chapter 1 Introduction

1.1 Background

Trucks, also referred to as heavy vehicles, may adversely affect the quality of traffic flow on a roadway. The negative impact trucks can have on the flow of traffic is likely due to: 1) the average space occupied by a truck, which is greater than that of a passenger car (e.g., the average gap in front and behind trucks is larger than those associated with passenger cars); and 2) the operational characteristics (e.g., acceleration, deceleration, maneuverability, etc.) of trucks, which are different, and typically lower, than that of passenger cars.

The Highway Capacity Manual (HCM) analysis and design procedures utilize Passenger Car Equivalents (PCE), also known as equivalency factors, to account for the presence of trucks in a traffic stream. The PCE represents the number of passenger cars that would have an equivalent effect on the quality of the traffic flow as any given truck would (Webster and Elefteriadou 1999). PCEs allow a heterogeneous mix of vehicles in a traffic stream to be expressed as a standardized homogenous traffic stream of passenger cars. By having an equivalent unit (e.g., passenger cars), traffic flows at different locations that experience various flows and percentages of vehicle types can be compared.

The current Highway Capacity Manual (HCM 2010) reports PCEs for a variety of roadway types, including multilane freeways and arterials. This report focuses on divided freeways, which corresponds to chapter 11 of the HCM 2010. The HCM provides PCE values for basic freeway segments and multilane highways as a function of grade percent, length of grade, and proportion of heavy vehicles up to 25 percent. A heavy vehicle in the HCM is defined in this repost as “a vehicle with more than four wheels touching the pavement during normal operation” in chapter 9 of the HCM 2010.

The current highway PCE factors in the 2010 HCM are based on a simulation study done in the late 1990s (Webster and Elefteriadou 1999). This study used FRESIM (v5.0) and an average-sized truck. The simulation was limited to situations where trucks comprised no more than 25 percent of vehicle traffic. A strength of this previous work was the use of traffic density to define PCEs using the methodology of Sumner et al. (1984), because density is the measure of effectiveness that is used to define the level of service for basic freeway segments in the 2010 HCM.

There are a number of reasons why the HCM values might not be valid for Nebraska conditions. For example, Interstate 80 (I-80) experiences truck percentages that can be as high as 60 percent. In addition, in the simulation study that was used to derive the HCM values, it was assumed that the free speed of all vehicle types is the same at level terrain. In Nebraska, a large proportion of trucks have been (voluntarily) outfitted with speed limiters that prevent the drivers from traveling at speeds in excess of approximately 67 mi/h. When a truck passes another, truck platoons may form, resulting in a delay for vehicles that are following, who may wish to be traveling at a faster speed. Lastly, it is unclear whether the “average” truck used in the simulation study is representative of a typical Nebraska truck.

The Nebraska Department of Roads (NDOR) requires HCM input data, including PCE, for their planning tools. These planning tools are used by NDOR planners and management to estimate future operating characteristics of I-80, and to plan for future expansion projects. The work in this report was conducted to identify whether the PCE values in the HCM are appropriate for Nebraska conditions and, if they are not, to recommend PCE values that would be more appropriate.

This research study will examine aspects of the current 2010 HCM PCE determination methodology to see if it is representative of Nebraska's traffic on basic freeway segments. To accomplish these tasks, field data was collected using ITS data collection equipment, including video and radar detectors. This data will be used to: 1) calculate PCEs using a variety of approaches, and 2) to calibrate a VISSIM traffic simulation model that can be used to estimate PCE values in a manner similar to that used to calculate the HCM values. It is intended that this study will investigate the accuracy, reliability, cost, and user-friendliness of various past PCE calibration methods for Nebraska conditions.

1.2 Objectives

The objective of this research is to estimate and recommend passenger car equivalents for basic freeway segments in Nebraska. The particular condition of concern for Nebraska is the high percentage of trucks and other heavy vehicles using Interstate 80 in the western regions of the state.

1.3 Organization

The report is organized into eight chapters. Chapter 1 provides relevant background information, and outlines the objectives of the study and organization of the report. Chapter 2 provides a literature review of PCE determination methods. Chapter 3 provides information about the data collection effort, including data collection sites, data collection equipment, and data collection conditions. Chapter 4 provides a preliminary analysis of the empirical data, including vehicle classifications, vehicle fleet composition, and observed speed distributions. Chapter 5 provides an overview of the 2010 HCM PCE methodology and estimates. The speed-volume relationship using the empirical data is compared to the HCM values. Chapter 6 provides platoon analyses using the empirical data. Definitions are provided for platoon, platoon type, and critical headway determination. Preliminary analyses for impeded, impeder, and non-impeded vehicles are also included. Lastly, three categories of platoon characteristics are described and analyzed. In Chapter 7, PCE values using empirical data are estimated using the headway-based method and the platoon-based method. In Chapter 8, a VISSIM model is created and calibrated for I-80 in western Nebraska. Subsequently, PCE values are calculated separately under different traffic flow conditions using a variety of approaches, including the HCM-based method, delay-based method, and headway-based method. In Chapter 9, the PCEs based on equal-density, delay, headway, and platoon methods under truck restriction conditions are calculated using these simulation data. Conclusions and recommended PCE values for I-80 in western Nebraska are provided in Chapter 10.

Chapter 2 Literature Review

2.1 Overview

The concept of passenger car equivalents (PCE) was first proposed in the 1950 HCM. PCE was first used for multilane highways. The PCE values were updated and expanded to other facilities in each of the following HCM editions. The methods for PCE determination on highway, freeway, and urban roads can be classified into four groups:

1. equal impedance method (e.g. equal speed method, equal density method, equal volume-capacity ratio method, equal travel time method, equal passenger-car travel time method),
2. ratio-based method (e.g. overtaking method, headway-based method, delay-based method, speed area-based method, travel time-based method),
3. regression-based method (e.g. platoon-based method, speed-based method, equal traffic flow or capacity method),
4. optimization method (e.g. queue discharge flow method).

The theory and logic behind these methods will be discussed in the following sections. The places where these methodologies have been used (e.g., two-lane highway, multilane highway, etc.) are summarized in table 2.1.

2.2 Equal Impedance Method

The basic idea behind the equal-impedance method is that the PCE is determined by comparing the volume for a given mixed traffic flow to a base flow (e.g. passenger-car-only) that has the same impedance. Note that any impedance metric could be used and previous research has examined speed, density, volume-capacity ratio, vehicle-hour, travel time and passenger car travel time (Huber 1982; Okura and Sthapit 1995; Elefteriadou et al 1997; Webster and Elefteriadou 1999). The basic approach was augmented by Sumner in 1984 by adding the concept of subjected flow. Subjected flow means a certain number of passenger cars in the mixed-traffic flow are replaced by an equal number of subject vehicles, which are defined as the vehicles for which a PCE will be estimated. The replacement proportion, Δp, is a decision variable, which is usually set to 5% (Sumner et al 1984). The PCE is estimated using equation 2-1. It may be seen that it is a function of the replacement proportion, Δp , and the base, mixed, and subject vehicle traffic flows that give the same impedance value c. The equal-impedance-based PCE is referred to as the E-PCE in the equation.

$$E - PCE = \frac{1}{\Delta p}\left(\frac{q_{Bc}}{q_{Sc}} - \frac{q_{Bc}}{q_{Mc}}\right) + 1 \qquad (2\text{-}1)$$

$E - PCE$	equal-impedance-based passenger car equivalents for subject vehicles
Δp	proportion of subject vehicles adding to the mixed flow and subtracted passenger cars from the mixed flow
q_{Bc}	flow rate at impedance c for base traffic flow
q_{Mc}	flow rate at impedance c for mixed traffic flow
q_{Sc}	flow rate at impedance c for subject vehicle traffic flow

The underlying logic is that the mixed flow and the base flow will produce the same impedance. This methodology is best illustrated by an example. Consider figure 2-1 where the y axis represents impedance and the x axis represents flow in terms of vehicles/hour. There are two impedance-flow curves shown in the figure. One curve (e.g. labeled “Base”) represents the basic flow with only passenger cars. The other curve (e.g. labeled “Mix”) shows the mixed traffic flow for the condition of interest (e.g., 90% passenger cars and 10% trucks). As would be expected, the impedance is higher for the mixed traffic flow than the base flow for a given vehicle flow rate (e.g., equal number of vehicles). Consider the situation where there is equal impedance as shown by the horizontal line. For the base case, this is represented as point A with a flow of q_{Bc} . For the mixed flow, this is point B with a flow of q_{Mc}. This can also been seen in point C, which is a subjected flow of q_{Sc} that has same impedance as q_{Bc} and q_{Mc}. These are the values used in Equation 2-1.

This method has been used for estimating PCEs for highways, urban roads, and freeways (Sumner et al 1984). Because of the large amount of specific data required, this approach is generally conducted using simulation data (Webster and Elefteriadou 1999). For example, data from TWOPAS and NETSIM have been used for estimating PCE values using the equal-speed method (Elefteriadou et al 1997; Torbic et al 1997). The simulation data from FRESIM has been used for calculating PCEs based on equal density impedance (Webster and Elefteriadou 1999). In general, it has been found that PCEs calculated using this method increase with grade, length of grade, traffic volume, truck length, and weight-to-power ratio, and decrease with truck percentage.

2.3 Ratio-Based Method

2.3.1 Overtaking Method

In the overtaking method, traffic data is collected from a series of representative roadway sections. The data is collected at a single point and includes vehicle type and vehicle speed. The vehicle type is based on the 1965 HCM. The passenger cars are categorized into several cohorts based on speed. The number of cohorts can vary from 8 to 15, although 10 is the recommend. The cohorts are ordered from the slowest cohort to the fastest. Trucks are categorized as belonging to a separate and single group. A truck is defined as a heavy vehicle engaged primarily in the transport of goods and materials or in the delivery of services other than public transportation. Note that a given vehicle is classified as either a truck or a passenger car (Werner and Morrall, 1976; Cunagin and Messer, 1982). It is assumed that only passenger car cohorts that have average speeds higher than the truck cohorts will produce overtaking maneuvers. It is further assumed that only the passenger cars in the faster cohorts can overtake the passenger cars in the slower cohorts.

The PCE is defined using equation 2-2. There are two parts to the equation. The first is the ratio of the frequency of passenger cars f_p to the frequency of trucks f_T. The second term is also a ratio. The numerator is an estimate of the number of passenger cars passing trucks. The denominator represents the estimate of the number of faster passenger cars passing slower passenger cars. The PCE is the product of the two ratios. The overtaking-based PCE is referred to as the O-PCE in the equation.

$$O - PCE = \left(\frac{f_p}{f_T}\right) * \frac{\sum_{j=T+1}^{N} f_T f_j \left[\left(\frac{1}{v_T}\right) - \left(\frac{1}{v_j}\right)\right]}{\sum_{i=1}^{N} \sum_{j=i+1}^{N} f_i f_j \left[\left(\frac{1}{v_j}\right) - \left(\frac{1}{v_i}\right)\right]} \qquad (2\text{-}2)$$

$O - PCE$	overtaking-based passenger car equivalents for trucks
f_p, f_T	frequency of passenger cars and trucks
f_i, f_j	frequency of passenger cars in cohort *i* (slower vehicle) and in cohort *j* (faster vehicle)
v_T	average speed of trucks
v_i, v_j	average speed of passenger cars in cohort *i* (slower vehicle) and in cohort *j* . Note that by definition the cohort j is traveling faster than the cohort i

The overtaking method was initially proposed for calculating PCEs on two-lane highways. It was first used to estimate PCEs for two-lane highways in the 1965 HCM.

It should be noted that the incidence of trucks passing cars that are traveling slower is ignored. In addition, there are not specific instructions for how to define the speed range for each cohort. It has been argued that PCEs calculated by this method are too high (e.g. higher than 100) for high grades (e.g., greater than 6%) and low level of service condition (e.g., LOS D and E) (Roess and Elena, 2014).

2.3.2 Headway-Based Method

Headway-based PCEs are based on the relationship between the spacing maintained by passenger car drivers in the proximity of trucks and the spacing maintained by passenger drivers in the proximity of passenger cars. It is hypothesized that these should be equivalent when considering the driver's perception of proximity to other vehicles and the freedom to maneuver. This concept is referred to as the driver's perception of equivalent densities. The assumption is that headways between passenger cars in base flow are equal to headways between passenger cars in mixed flow (Krammes and Crowley, 1986). The Equation 2-3 shows the equation used for the headway-based method. The denominator, h_{pp}, represents the mean headway of passenger cars following passenger cars. The numerator is comprised of two terms. The first term is the product of the percentage of non-trucks in the traffic stream and the sum of the mean headways for passenger cars following trucks, the mean headway of trucks following passenger cars, and the negative of the mean headway of passenger cars following passenger cars. The second term is the product of the percentage of trucks in the traffic stream and the mean headways or trucks following trucks. The headway-based PCE is referred to as the H-PCE in the equation.

$$H-PCE \ = \frac{(1-p)(h_{pt}+h_{tp}-h_{pp})+p*h_{tt}}{h_{pp}} \qquad (2\text{-}3)$$

$H-PCE$	headway-based passenger car equivalents for trucks
p	percentage of trucks at a mixed traffic stream
h_{pp}	mean headway for passenger cars following passenger cars (seconds)
h_{pt}	mean headway for passenger cars following trucks (seconds)
h_{tp}	mean headway for trucks following passenger cars (seconds)
h_{tt}	mean headway for trucks following trucks (seconds)

It may be seen in Equation 2-3 that if h_{tp}, h_{pt} and h_{tt} are the same as the h_{pp} then the PCE will be one. The more the heavy vehicle affects the headway of the following passenger car, the higher the PCE. This method is used to calculate PCE for one lane of a highway, urban road, or freeway (Krammes and Crowley, 1986). Note that either leading or lagging headways can be used in Equation 2-3. The leading headway includes the length of the vehicle and the inter-vehicle space behind the vehicle. The lagging headway includes the length of the vehicle, and the inter-vehicle space precedes the vehicle. In Krammes' research, the lagging headway is used

(Krammes and Crowley, 1986).

It is assumed that the headways are for vehicles that are interacting with each other. For example, vehicles that are following each other but are five minutes apart would not be used. This means that a critical headway, which is the threshold for vehicle interaction, must be defined as a *priori* knowledge. These values range from 2s to 8s in the literature (Miller, 1961; Keller, 1976; Fitzpatrick et al 2004; Al-Kaisy and Karjala 2010).

2.3.3 Delay-Based Method

The delay-based PCE method is shown in equation 2-4. The PCE is a ratio of the amount of delay caused by a given amount of trucks in a given flow to the delay resulting from the same flow, which consists of all passenger cars (Benekohal and Zhao 2000). In essence, the PCE represents how many passenger cars could replace a given truck and result in the same amount of delay to all vehicles. The delay-based PCE is referred to as the D-PCE in the equation.

$$D - PCE = 1 + \frac{\Delta d_t}{d_0} \tag{2-4}$$

$D - PCE$	delay-based passenger car equivalents for trucks
Δd_t	additional delay caused per truck (seconds)
d_0	average delay per vehicle of passenger car when truck percentage is 0% (base delay) (seconds)

This equation was initially proposed for PCE determination at signalized interactions (Zhao, 1996). It was extended for estimating PCE on work zone areas on the highway (Chitturi and Benekohal, 2007), as shown in equation 2-4.

This method can only be used where this is a strict lane-following discipline (e.g., no passing). Consequently, it has been used for calculating PCEs at signalized interactions, work zones, platoons, and traffic incident locations where there are fairly severe drops in speed.

2.3.4 Speed-Area-Based Method

This method is based on a ratio, as shown in equation 2-5. The numerator is the ratio of the mean speed for passenger cars to the mean speed of trucks. The denominator is the ratio of projected rectangular areas (e.g., product of length and width) on the road for passenger cars to the projected rectangular areas on the road for trucks (Chandra and Sikdar, 2000). As might be suspected from the equation, this model is used where lane discipline is not maintained and where the number of vehicles on a cross-section may be greater than the number of lanes. This occurs in many developing countries where small cars, auto rickshaws, and motorcycles have significant market penetration. This method attempts to capture the lateral and longitudinal space usage of different vehicle types. In the U.S., where lane discipline is universally maintained, it would not be useful because it is assumed that a given vehicle will occupy the entire lane regardless of its size. The speed-area-based PCE is referred to as the SA-PCE in the equation.

$$SA - PCE = \frac{V_c/V_i}{A_c/A_i} \tag{2-5}$$

$SA - PCE$	speed-area-passenger car equivalents for trucks
V_c	mean speed for passenger cars (mph)
V_i	mean speed for vehicle type *i* (mph)
A_c	projected rectangular areas on the road for passenger cars (ft^2)
A_i	projected rectangular areas on the road for vehicle type *i* (ft^2)

The speed area-based method was initially proposed for estimating PCEs on Indian urban road conditions. It has subsequently been widely used in developing countries where lane-discipline is not followed and where there is a high degree of mixed traffic volume (e.g., non-motorized vehicles, two-wheeler vehicles, and three-wheeler vehicles). It is hypothesized that this method may not be appropriate for traffic conditions in the U.S.

2.3.5 Travel-Time-Based Method

The travel-time-based PCE method is shown in equation 2-6. It may be seen that the PCE is defined as the ratio total travel time of a given vehicle type over a section of roadway to the total travel time of the base vehicle (e.g., passenger car) over the same section (Keller and Saklas 1984). Note that the “section” could consist of the entire network. The travel-time-based PCE is referred to as the T-PCE in the equation.

$$T - PCE_i = \frac{TT_i}{TT_b} \tag{2-6}$$

$T - PCE_i$	travel-time-based passenger car equivalents for vehicle type *i*
TT_i	total travel time of vehicle type *i* over the network (seconds)
TT_b	total travel time of base vehicle (passenger car) over the network (seconds)

This method was proposed for PCEs on highway and urban roads. In this method, the travel time can include two parts: the travel time for the link (road midway), and the travel time for traveling through intersections (including stop delay). Because this is approach is very data intensive, it has historically been used with simulated data (Keller and Saklas 1984). For example, TRANSYT was used to calculate PCEs for intersections (Brooks 2010).

2.4 Regression-Based Method

2.4.1 Platoon-Based Method

The platoon-based PCE is calculated using equations 2-7 and 2-8. It may be seen that the PCE is the ratio of the number of followers caused by a given vehicle type (e.g., truck, bus, motorcycle) to the number of followers caused by a passenger car (Van Aerde and Yagar 1984). In essence, the approach attempts to identify the number of passenger cars that would replace a given vehicle type in the traffic stream and result in the same amount of followers. The platoon-based PCE is referred to as the P-PCE in the equation.

$$V_f = a + \sum_{i=0}^{n} b_i V_i \tag{2-7}$$

$$P - PCE_i = \frac{b_i}{b_0} \tag{2-8}$$

$P - PCE_i$	platoon-based passenger car equivalents for vehicle type i
V_i	traffic volume of vehicle type i ; for passenger car, i = 0.
V_f	average number of followers in platoons
a, b_i	regression coefficients for vehicles of type i. Note that for passenger car, i is set equal to 0

The PCEs are based on an average number of followers, which is modeled by a linear regression equation. In essence, the modeler must collect data on a number of platoons that are led by vehicles of varying types. This data is used to estimate the parameters.

The platoon-based method was initially proposed for PCE determination on two-lane highways, where passing lead vehicles may be difficult if there is a considerable amount of on-coming vehicles and/or many locations of restricted sight lines. There is no set definition for what constitutes a platoon. Typically, a critical headway, similar to that described in section 2.3, is used. These values have varied from 2s to 8s (Miller 1961; Keller 1976; Fitzpatrick et al 2004). A critical factor identified in the literature is that the independent variable (e.g. V_{car}, V_{truck}, V_{bus}) may be correlated. If this is true, the standard errors of the coefficient may be too high, which would lead to unreliability in the estimated coefficients (Gunst and Weber 1975).

2.4.2 Speed-Based Method

The speed-based PCE approach is shown in equations 2-9 and 2-10. It may be seen that the PCE is the ratio of the amount of speed reduction in a traffic stream caused by a given vehicle type to the amount of speed reduction caused by a passenger car (Van Aerde and Yagar, 1984). In essence, this ratio represents the number of passenger cars that would replace a given vehicle type and result in the same amount of speed reduction. The speed-based PCE is referred to as the S-PCE in the equation.

$$S_{percentile} = S_F + \sum_{i=0}^{n} c_i V_i \quad (2\text{-}9)$$

$$S - PCE_i = \frac{c_i}{c_0} \quad (2\text{-}10)$$

$S - PCE_i$	speed-based passenger car equivalents for vehicle type i
V_i	traffic volume of vehicle type i ; for passenger car, i = 0.
$S_{percentile}$	percentile speed (mph)
S_F	free flow speed (mph)
c_i	regression coefficient; for passenger car, i = 0

The PCEs are based on estimated speeds as modeled by a linear regression equation. The estimated speed may be average, 50th percentile (median), 90th percentile, 95th percentile, etc. In essence, the modeler must collect data on vehicle speed and traffic composition (e.g. number of vehicles of each type). This data is used to estimate the parameters. This approach does not rely on defining a platoon.

This method was initially proposed for PCE determination on two-lane highways. Similar to the platoon-based method, a critical factor identified in the literature is that the independent variable (e.g. $V_{car}, V_{truck}, V_{bus}$) may be correlated. If this is true, the standard errors of the coefficient may be too high, which would lead to unreliability in the estimated coefficients (Gunst and Weber 1975).

2.4.3 Equal Traffic Flow/Capacity Method

This method is shown in equation 2-11. In essence the PCE represents the number of passenger cars that would replace a truck in a given mixed traffic stream. It is assumed that the mixed stream would produce the same traffic conditions (e.g., travel time, speed, density, etc.) as a passenger-car-only traffic stream that was developed based on the PCE (Alecsandru et al 2012). In this instance, the goal is to have the PCE-based passenger-car-only stream replicate the mixed traffic stream for all traffic flow conditions. Note that in other approaches the researchers are only concerned with traffic flow at capacity (e.g., LOS E) (Fan 1990). The generalized form of the conversion from the mixed traffic flow to the passenger-car-only flow is provided in equation 2-11. The equal-flow/capacity-based PCE is referred to as the EF-PCE in the equation.

$$MSF_i N = E_{car} P_{car} F + \sum_j E_j P_j F, \; EF - PCE_i = \frac{E_j}{E_{car}} \quad (2\text{-}11)$$

$EF - PCE_i$ equal-flow/capacity-based passenger car equivalents for vehicle type i

MSF_i	maximum service flow rate at LOS *i* under ideal conditions (capacity for LOS i) in passenger cars per hour per lane
N	number of lanes
F	observed traffic volume (veh/h)
E_{car},E_j	regression coefficients for passenger cars and vehicle type *j*
P_{car}, P_j	percentage of passenger cars and vehicle type j

The product of MSF_i and N is the total passenger car throughput for the base case scenario (passenger-car-only flow) at the road segment clearance time (or at intersection discharging time). One difficulty this method poses is correctly defining the capacity or finding the maximum traffic flow for the base case at a specific condition. The equal capacity method performs well for both field and simulation data, while the equal-flow method performs better for simulation data due to difficulties in collecting a large amount of base case data at a given time in the field. Potential multicollinearity and intercorrelations between independent variables may also exist (Gunst and Weber 1975).

2.5 Optimization Method (Queue Discharge Flow Method)

In the queue discharge flow (QDF) method, the QDF capacity is considered to be the equivalent criterion because it governs the operation of the freeway after the onset of congestion. This means that if trucks in the mixed stream are converted to passenger cars based on a QDF-based PCE, the converted QDF capacity is expected to have minimal variation (Al-Kaisy et al 2002; Al-Kaisy et al 2005). The objective is the minimum of variation for PCE-based converted QDF capacity. The design variable is the PCE, with constraints between the lowest and highest values of QDF capacities and PCEs. The goal is to find the optimal value that minimizes the variation for the converted QDF capacity. The QDF method is shown as a mathematical program in equation 2-12. The queue-discharge-flow-based PCE is referred to as the QDF-PCE in the equation.

Objective Function: $Minimize\ Z(C^*)$
Design Variable: $QDF - PCE$ (2-12)
Constrains: $X1 \leq C^* \leq X2, X3 \leq PCE \leq X4$

$QDF - PCE$	queue-discharge-flow-based passenger car equivalents
C^*	Queue discharge flow capacity
$Z(C^*)$	coefficient of variation for converted QDF capacity
$X1, X2$	lower and upper limit of QDF capacity
$X3, X4$	lower and upper limit of passenger car equivalents

Based on the definition, this method is only appropriate for PCE determination under the congestion condition (e.g. work zone area or bottleneck on freeways and highways). One issue is that it is not clear how the lower and upper limits of passenger car equivalents should be determined.

2.6 Concluding Remarks

This chapter provided an overview of eleven common PCE estimation methods. The equal-density method, which is based on the equal impedance method, was used to estimate highway and freeway PCE values for the 2000 and 2010 HCM. In chapter 7 and 8, the equal-density method will be used for PCE determination under high truck percentage conditions for I-80 in Nebraska. The appropriateness of the HCM approach for Nebraska will be discussed. In addition, the headway-based method (section 2.3.2) and delay-based method (section 2.3.3) will be analyzed using Nebraska data. These approaches were chosen based on 1) their underlying theory and 2) an analysis of Nebraska data as will be discussed in chapter 3 and 4. The next chapter will discuss the data collection effort.

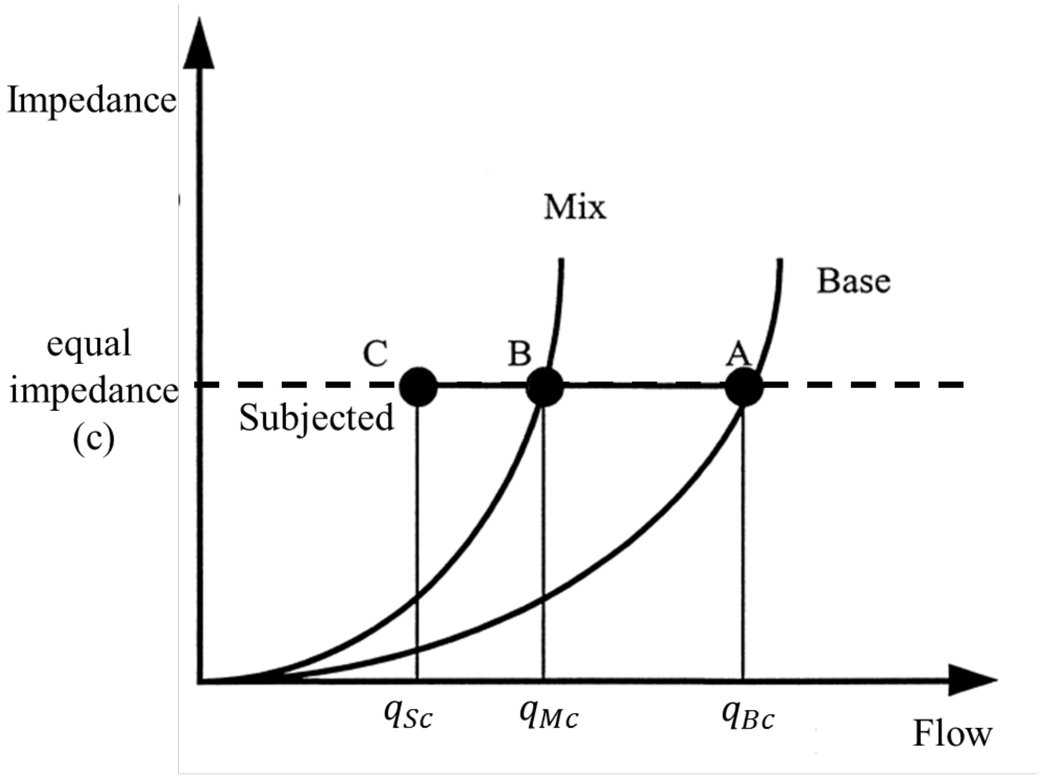

Figure 2.1 Impedance-flow relationship for equal impedance method

Table 2.1 Summary of places that PCE methodologies used

Method	**Two-Lane Highway**	**Multilane Highway**	**Freeway**	**Urban Road**
Overtaking	Werner and Morrall, 1976; Cunagin and Messer, 1982			
Equal Impedance	Huber, 1982	Okura and Sthapit, 1995; Elefteriadou et al, 1997; Torbic et al, 1997; Webster and Elefteriadou, 1999	Okura and Sthapit, 1995; Elefteriadou et al, 1997; Torbic et al, 1997; Webster and Elefteriadou, 1999	Sumner et al, 1984
Headway	Werner and Morrall, 1976	Krammes and Crowley, 1986	Krammes and Crowley, 1986	Molina, 1987
Delay		Chitturi and Benekohal, 2007	Chitturi and Benekohal, 2007	Zhao, 1996; Benekohal and Zhao, 2000
Platoon	Van Aerde and Yagar, 1984			
Speed Area				Chandra and Sikdar, 2000
Speed	Van Aerde and Yagar, 1984			
Travel Time				Keller and Saklas, 1984
Equal Traffic Flow		Alecsandru et al, 2012	Alecsandru et al, 2012	
Equal Traffic Capacity		Fan, 1990; Yeung et al, 2015	Fan, 1990; Yeung et al, 2015	
Queue Discharge Flow		Al-Kaisy et al, 2002; Al-Kaisy et al, 2005	Al-Kaisy et al, 2002; Al-Kaisy et al, 2005	

Chapter 3 Data Collection

3.1 Data Collection Sites

Data was collected on Interstate 80 at 13 locations between mileposts 177 and 399, as shown in figure 3.1. This 222-mile section is located between Lincoln and North Platte. Interstate 80 is a divided four-lane freeway with a speed limit of 75 mph.

The goal was to find data collection sites that were similar to each other but experienced different volumes and truck percentages. Table 3.1 provides a description of the attributes of the 13 sites. All of the test sites, which had two 12-foot lanes in each direction and a 6-foot lateral clearance on the right lane, had level terrain (e.g., grades less than 1%) and were straight (e.g., no horizontal curvature). As will be discussed later, it was critical that the traffic information was collected from an overpass. Consequently, the data collection site was located on an overpass and information was collected from the traffic below. Five of the sites had entrance and exit ramps for Interstate 80, and eight did not. Data was collected for a single direction. A detailed description of each site is given in Appendix A.

3.2 Data Collection Methodology

3.2.1 Equipment

Data were collected using the Nebraska Transportation Center's (NTC) mobile data collection equipment and the NTC ITS van. The van is equipped with two cameras mounted on a 42-foot telescope mast, as well as Autoscope, a video detection system. In the field, the van was parked on the overpass above I-80 with cameras directed straight down in order to obtain the best view of the two lanes. Figure 3.2 shows a picture of the van during data collection at the overpass in Milford.

The Autoscope system was used to collect speed data. Virtual speed detectors were directly set on the video, and these were located in the middle of each lane, as shown in figure 3.3. When the front bumpers of the vehicles reached the front edge of virtual detectors, the detectors were activated until the rear bumpers were no longer in the detection zone. The detectors were used to measure instantaneous speed and occupancy. Autoscope uses the occupancy and speed information to estimate vehicle length and, based on vehicle length, the vehicle type. The raw data included the vehicle count, the time at which vehicles entered and left detectors (millisecond), and vehicle speed (mph). Vehicles were classified into five categories that corresponded to the FHWA 13-Category Rule Set (FHWA 2014): passenger cars (including normal passenger cars, pick-ups, panel vehicles, and vans as well as vehicles with one or two axle trailers), buses, single-unit trucks, heavy trucks, and recreational vehicles. Data collection results were automatically output into an ASCII.txt file by Autoscope.

3.2.2 Sensor Calibration

The sensors were calibrated prior to each day's data collection in order to ensure the most accurate results as possible. In particular, the following Autoscope parameters were calibrated: (1) the critical length for vehicle type identification, (2) the minimum and maximum detected vehicle speeds, and (3) the length, width, and position of virtual speed detectors. Critical length is used for identifying differences in length among the five vehicle classifications. Vehicles with a length no longer than 25 feet were identified as passenger cars; vehicles with a length between 25 feet and 35 feet were identified as buses, single unit trucks, or recreational vehicles; and those with a length longer than 35 feet were identified as heavy trucks. Due to similarities in length among buses, single-unit trucks, and recreational vehicles, these three classifications were manually identified from the video recording through a two-step process. First, the time stamp for each vehicle over 35 feet was identified. Then, a viewer examined the tape and classified the vehicle accordingly.

As part of the calibration, minimum and maximum detected speeds need to be identified. Prior to data collection, the preliminary data was collected. It was found that the minimum and maximum speeds were between 45 mph and 50 mph, and between 95 mph and 100 mph, respectively. In order to effectively identify outliers in output data, the minimum and maximum detected speeds were set as 0 mph and 120 mph, respectively, so that the complete range of speeds could be observed.

The length, width, and position of virtual speed detectors were calibrated according to Autoscope calibration protocol (Michalopoulos 1991). First, an image of the data collection site was obtained, which is known in the literature as “snapped on.” Critical data, including lane width, length of observing freeway segments, and height of the cameras, was measured in the field. A set of three horizontal and three vertical grid lines were placed on the image. The length and width were calibrated using the gird lines as references. The distance between two adjacent vertical lines was set to represent lane width. These values were set to 0 feet, 12 feet, and 24 feet from the left vertical grid line to the right grid line. These values were set from left to right so that the left grid line would represent the base line: the 0 foot position. The distance between two adjacent horizontal lines represents the length of the measured freeway segment. Prior to data collection, three markings were placed on the highways, located 30 feet apart, and these markings were used as guides. The horizontal distances were set to 0 feet, 30 feet, and 60 feet. These markings were made from top to bottom where the top is the base condition, or 0 foot position. The height of the cameras represents the distance between the cameras and the highway and includes the height of the overpass, the height of the van, and the height of the mast. These heights were measured at each site, and the average value was 47 feet.

3.3 Data Collection

The empirical data was collected at 15 separate locations over 15 separate days during the period from June 1 through December 22, 2015. The data was collected during:

1. daytime hours ranging from 8:00 am to 7:00 pm in the summer and 9:00 am to 5:00 pm in the fall;
2. clear weather conditions with dry pavements (e.g., no rain or snow) and cloudy conditions, which minimized the effect of vehicle shadows on the accuracy of the detector; and
3. wind speeds that were below 10 mph. Strong continuous winds or wind gusts were capable of swaying the van’s mast, producing erroneous data, and decreasing safety.

In total, 60 hours of valid traffic flow data were collected, with an average of 4.6 hours for each site. Details for the data collection condition and results are shown in table 3.2. It may be seen that the amount of vehicles observed hourly decreases from east to west on Interstate 80.

3.4 Concluding Remarks

Once the data was collected a preliminary analysis was conducted as will be discussed in Chapter 4.

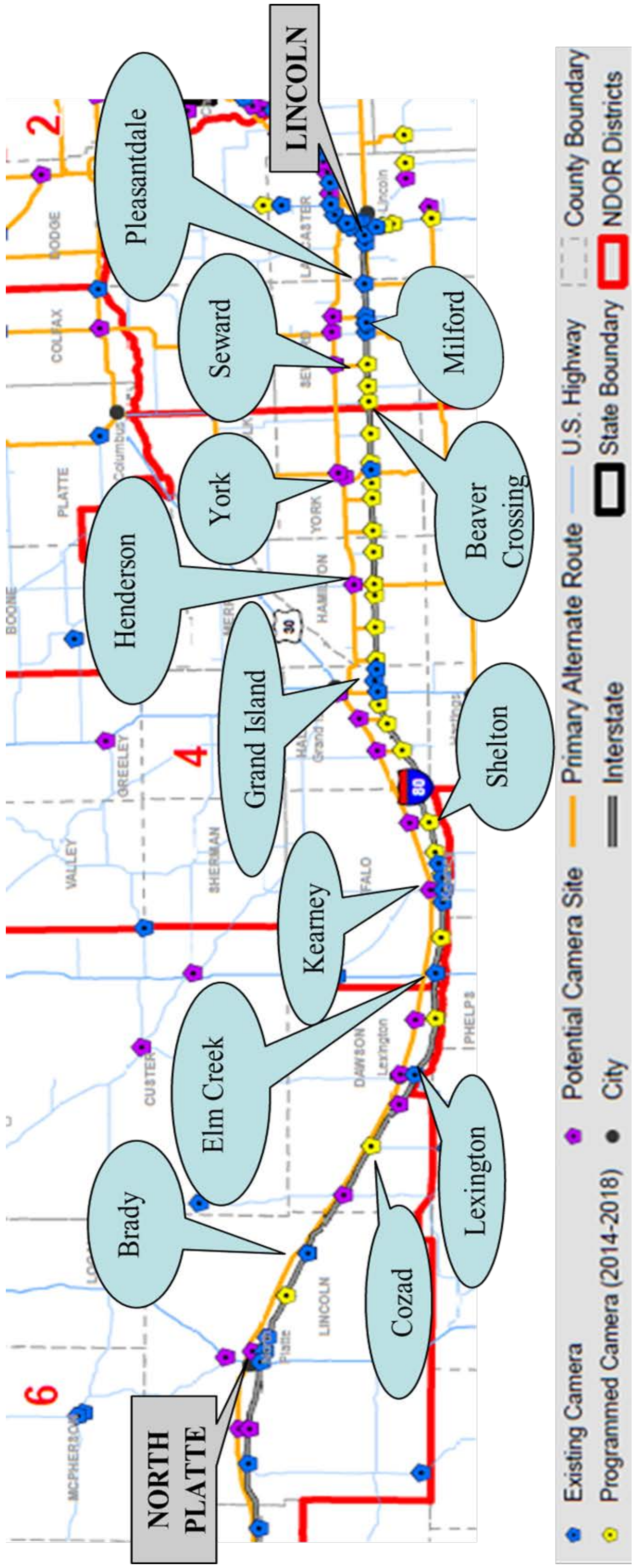

Figure 3.1 I-80 Data collection sites between Lincoln and North Platte

Figure 3.2 NTC's ITS data collection van

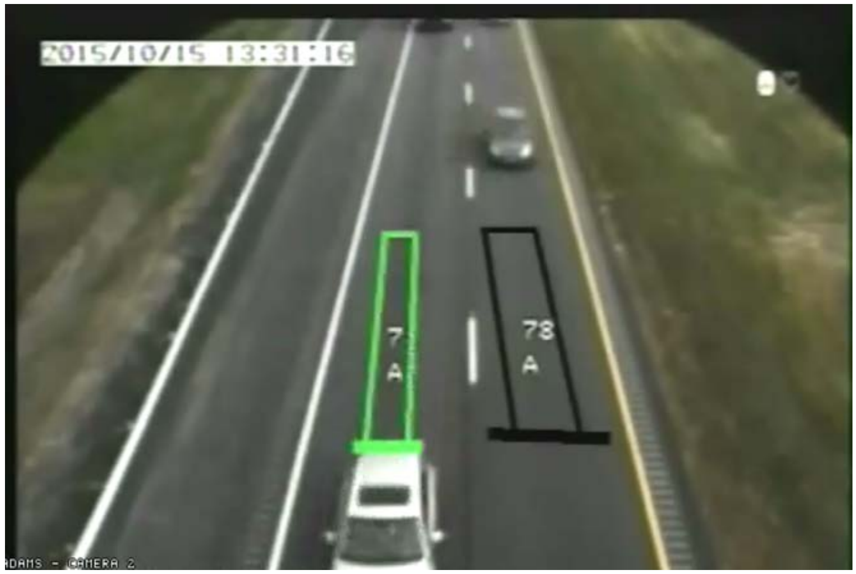

Figure 3.3 Layout of virtual speed detectors on video

Table 3.1 Data collection sites along I-80 on western part of Nebraska, between Lincoln and North Platte

Data Collection Site	Mile Marker	Camera Height (ft)*	Overpass Road	Direction*	Nearest Exit
Pleasantdale	388	47.0	County Hwy 154 / State Hwy 103	WB	-
Milford	382	47.0	County Hwy 238 / State Hwy 80H	WB	-
Seward	378	46.5	County Hwy 294	EB	Exit 379
Beaver Crossing	369	46.8	County Hwy 420 / State Hwy 80E	WB	-
York	354	47.5	Rd M	WB	Exit 353
Henderson	342	48.0	State Hwy 93A	WB	-
Grand Island	316	47.1	County Hwy 4	WB	Exit 318
Shelton	290	47.7	Willow Rd	EB	Exit 291
Kearney	280	47.0	M Ave	WB	Exit 279
Elm Creek	255	48.2	450 Rd	WB	Exit 257
Lexington	234	47.0	Rd 431	WB	Exit 237
Cozad	220	46.0	Rd 419	WB	Exit 222
Brady	199	46.5	56D / S Banner Rd.	WB	-

*Camera is located “Camera Height” feet above the roadway; “WB” means westbound, and “EB” means eastbound.

Table 3.2 Summary of data collection

Data Collection Sites	Date (in 2015)	Hours	Total Duration (hours)	Number of Vehicles Observed
Pleasantdale	Monday, June 01	4:00 PM to 7:00 PM	3	2695
Milford	Wednesday, June 10	5:00 PM to 6:00 PM	1	886
	Friday, June 12	11:00 AM to 3:00 PM	4	4576
	Tuesday, September 29	1:00 PM to 4:00 PM	3	3175
Seward	Friday, June 12	4:00 PM to 7:00 PM	3	3886
	Tuesday, June 16	10:00 AM to 12:00 PM	2	1690
Beaver Crossing	Friday, November 13	12:00 PM to 3:00 PM	3	3104
York	Tuesday, June 16	3:00 PM to 7:00 PM	4	3284
	Friday, June 19	12:00 PM to 3:00 PM	3	3655
Henderson	Thursday, October 15	1:00 PM to 4:00 PM	3	2357
Grand Island	Wednesday, November 25	11:00 AM to 3:00 PM	4	4610
Shelton	Wednesday, June 03	1:30 PM to 6:30 PM	5	3958
Kearney	Tuesday, December 22	9:00 AM to 1:00 PM	4	2061
Elm Creek	Monday, December 21	12:00 PM to 4:00 PM	4	2055
Lexington	Friday, November 20	9:00 AM to 1:00 PM	4	2055
Cozad	Thursday, November 15	1:30 PM to 5:30 PM	4	1920
Brady	Tuesday, June 02	1:00 PM to 7:00 PM	6	3059
Total			**60**	**48903**

Chapter 4 Preliminary Analysis

4.1 Vehicle Classification

In this research, the vehicle classification is based on the FHWA 13-Category Rule Set. This standardized vehicle classification system was developed by FHWA in the mid-1980s, and it is currently used for most federal reporting requirements and serves as the basis for most state vehicle classification counting efforts (FHWA 2014). The classification is shown in figure 4.1. According to this standard, vehicles are classified into the following 6 groups: motorcycles (class 1); passenger cars, pickups, vans, and vehicles with trailers (classes 2 and 3); buses (class 4), single-unit trucks (classes 5, 6, and 7); recreational vehicles (class 5); and heavy trucks (classes 8 to 13).

4.2 Vehicle Composition

The numbers of observed vehicles for each vehicle classification and data collection site are shown in table 4.1. A total of 48,903 vehicles were observed across the 13 data collection sites. The data included 34,330 passenger cars, 14,231 trucks (1,287 single-unit trucks and 12,944 heavy trucks), 261 buses, and 81 recreational vehicles. The observed vehicles are mainly comprised of passenger cars (70.2%) and trucks (29.1%). Buses and recreational vehicles were 0.7% of the traffic flow and therefore only the effect of trucks on the traffic flow was analyzed. Note that 91% of the truck traffic was identified as heavy trucks.

The hourly volume of each vehicle classification at all of the data collection sites are shown in table 4.2 and figure 4.2. The results of the data are detailed below.

a) The hourly traffic volume decreases from east to west. East of Shelton, the traffic volume is greater than 1000 veh/h, and west of Shelton, it is lower than 1000 veh/h.

b) Passenger car hourly traffic volume decreases from east to west. This decrease is at a much greater rate than that of trucks. East of Shelton, passenger car volume is greater than 500 veh/h, and west of Shelton it is less than 500 veh/h. Truck volume varies between 100 to 300 veh/h across all sites.

c) Hourly volume for both buses and recreational vehicles are very low at all data collection sites, compared with passenger cars and trucks.

The percentages of vehicles for each classification at all of the sites are shown in table 4.3 and figure 4.3. The data results are provided below.

a) From east to west the truck percentage gradually increases while the passenger car percentage gradually decreases. East of Grand Island, the truck percentage ranges from 19.4% to 31.7%; west of Grand Island, it ranges from 27.4% to 46.2%.

b) Truck percentages are higher than 25% (the highest truck percentage in the HCM 2010) at 10 of 13 sites. Note that the average truck percentage for all of the data collection sites is 30%.

c) The percentage of both buses and recreational vehicles are very low at all data collection sites, compared with passenger cars and trucks.

Tables 4.2-4.3 and figures 4.2-4.3 show the results for hourly volume and truck percentage, the details of which are provided below.

a) On I-80 between Lincoln and North Platte, Nebraska, a lower truck percentage (less than 30%) usually appears with a higher traffic volume (higher than 1000 veh/h) east of Grand Island. In contrast, a higher truck percentage (higher than 30%) usually appears with a lower traffic volume (lower than 1000 veh/h) west of Grand Island.

b) Approximately 10% of the percentage of single-unit trucks are heavy trucks. It would be expected that heavy trucks have a much greater effect on traffic than single-unit trucks.

4.3 Speed Distribution

The 15th percentile, average, and 85th percentile of speed distributions for passenger cars, single-unit trucks, and heavy trucks are shown in figure 4.4. Based on the collected data, the average speed of a passenger car and a truck is 71.6 mph and 64.5 mph, respectively. The average speed of a passenger car is 7.1 mph higher than that of a truck, and this difference is statistically significant at the 95% level of confidence ($t = 122.28$, $P < 0.05$). The average speed of a single-unit and a heavy truck is 65.9 mph and 64.3 mph, respectively. The average speed of a single-unit truck is 1.6 mph higher than that of a heavy truck, and this difference is statistically significant at the 95% level of confidence ($t = 9.66$, $P < 0.05$). While the difference was statistically significant, it was determined that the difference was low enough that the group could be combined.

The 85th percentile speed for a passenger car, single-unit, and heavy truck is 77 mph, 72 mph, and 70 mph, respectively. The 85th percentile speed for a passenger car is 2 mph higher than the maximum speed limit on I-80 in Nebraska (e.g., 75 mph). The 15th percentile speed for a passenger car, single-unit, and heavy truck is 66 mph, 59 mph, and 58 mph, respectively. The 15th percentile speed for all vehicle classifications are higher than the minimum speed limit on I-80 in Nebraska (e.g., 40 mph).

4.4 Concluding Remarks

In this chapter, the vehicle composition and speed distribution statistics were provided. The vehicle classification is based on the FHWA 13-Category Rule Set and divided into five classifications: passenger cars, single-unit trucks, heavy trucks, buses, and recreational vehicles. The vehicle stream consists mainly of passenger cars (70.2%) and trucks (29.1%). The results of vehicle composition analysis show that hourly traffic volume gradually decreases while truck percentage gradually increases from east to west. A lower truck percentage (less than 30%) occurs periodically east of Grand Island where traffic volumes are higher (e.g., greater than 1000 veh/h). A higher truck percentage (higher than 30%) occurs periodically west of Grand Island where traffic volumes are lower (lower than 1000 veh/h). Also, due to 91% of the truck traffic identified as heavy trucks and the low speed difference between single-units and heavy trucks, these two vehicle classifications can be combined for analysis.

Table 4.1 Total number of vehicles for each classification

Data Collection Sites	PC (Passenger Car)	ST (Single-unit Truck)	HT (Heavy Truck)	Truck (ST+HT)	Bus	RV (Recreational Vehicle)	Total
Pleasantdale	2080	58	535	593	16	6	2695
Milford	6154	266	2168	2434	34	15	8637
Seward	4286	132	1126	1258	29	3	5576
Beaver Crossing	2275	54	759	813	14	2	3104
York	4934	162	1786	1948	41	16	6939
Henderson	1590	49	697	746	16	5	2357
Grand Island	3703	73	821	894	11	2	4610
Shelton	2583	141	1191	1332	21	22	3958
Kearney	1438	49	566	615	7	1	2061
Elm Creek	1486	35	527	562	6	1	2055
Lexington	1168	53	695	748	13	3	1932
Cozad	1013	43	844	887	19	1	1920
Brady	1620	172	1229	1401	34	4	3059
Total	34330	1287	12944	14231	261	81	48903

Table 4.2 Hourly volumes for each vehicle classification on all data collection sites (veh/h)

Data Collection Sites	PCs	STs	HTs	Trucks	Buses	RVs	Total Volume
Pleasantdale	693	19	178	197	5	2	1094
Milford	769	33	271	304	4	2	1383
Seward	857	26	225	251	6	1	1366
Beaver Crossing	758	18	253	271	5	1	1306
York	705	23	255	278	6	2	1269
Henderson	530	16	232	248	5	2	1033
Grand Island	926	18	205	223	3	1	1376
Shelton	517	28	238	266	4	4	1057
Kearney	360	12	142	154	2	0	670
Elm Creek	372	9	132	141	2	0	656
Lexington	292	13	174	187	3	1	670
Cozad	253	11	211	222	5	0	702
Brady	270	29	205	234	6	1	745
Average	562	20	209	229	4	1	1025

* Note: PC = passenger car; ST = single-unit truck; HT = heavy truck; RV = recreational vehicle

Table 4.3 Percentage of vehicles for each classification

Data Collection Sites	% PCs	% STs	% HTs	% Trucks	% Buses	% RVs
Pleasantdale	77.2%	2.2%	19.9%	22.0%	0.6%	0.2%
Milford	71.3%	3.1%	25.1%	28.2%	0.4%	0.2%
Seward	76.9%	2.4%	20.2%	22.6%	0.5%	0.1%
Beaver Crossing	73.3%	1.7%	24.5%	26.2%	0.5%	0.1%
York	71.1%	2.3%	25.7%	28.1%	0.6%	0.2%
Henderson	67.5%	2.1%	29.6%	31.7%	0.7%	0.2%
Grand Island	80.3%	1.6%	17.8%	19.4%	0.2%	0.0%
Shelton	65.3%	3.6%	30.1%	33.7%	0.5%	0.6%
Kearney	69.8%	2.4%	27.5%	29.8%	0.3%	0.1%
Elm Creek	72.3%	1.7%	25.6%	27.4%	0.3%	0.1%
Lexington	60.5%	2.7%	36.0%	38.7%	0.7%	0.2%
Cozad	52.8%	2.2%	44.0%	46.2%	1.0%	0.1%
Brady	53.0%	5.6%	40.2%	45.8%	1.1%	0.1%
Average	68.5%	2.6%	28.2%	30.7%	0.6%	0.2%

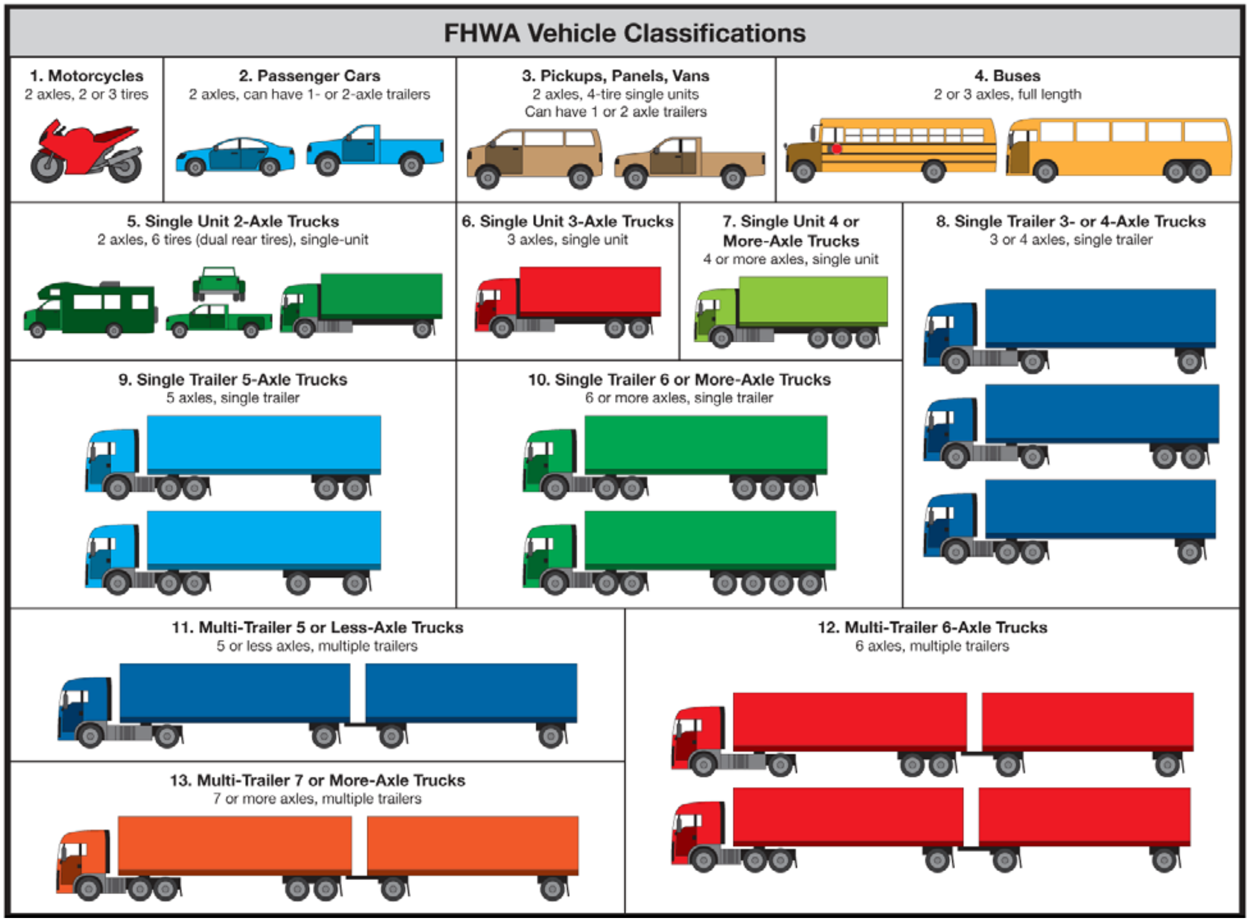

Figure 4.1 FHWA 13-category vehicle classifications

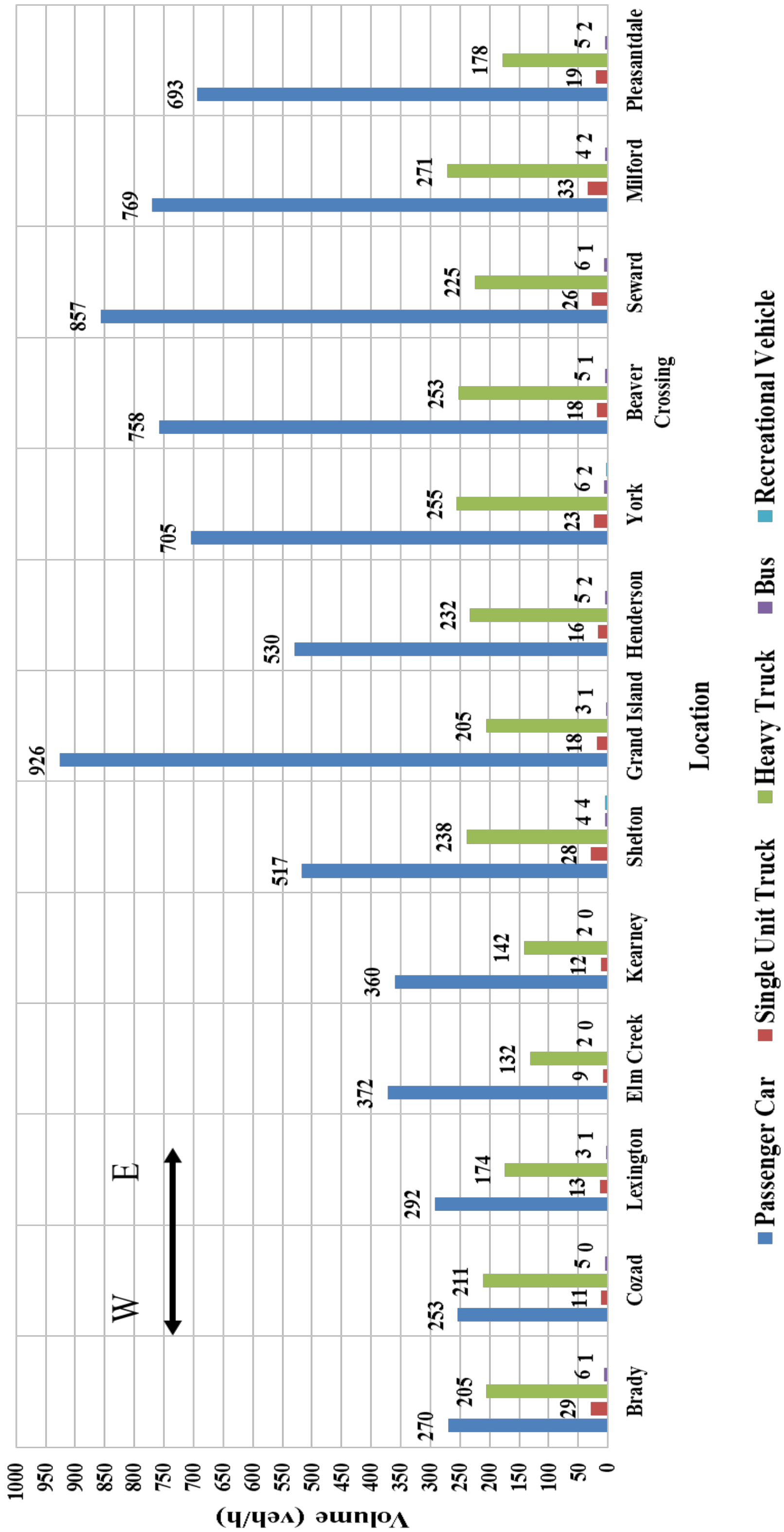

Figure 4.2 Hourly volumes for each classification

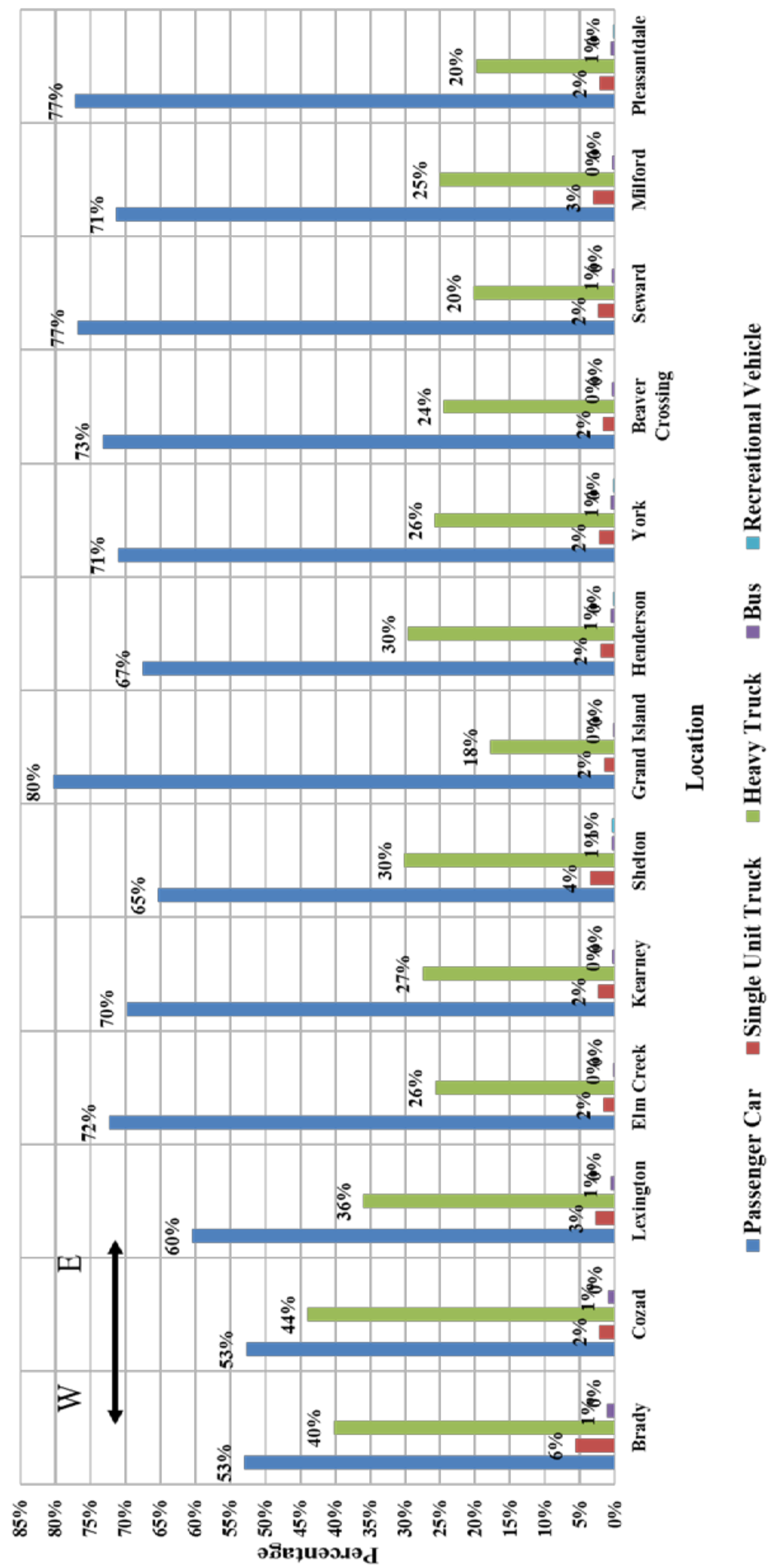

Figure 4.3 Percentage of vehicles for each classification

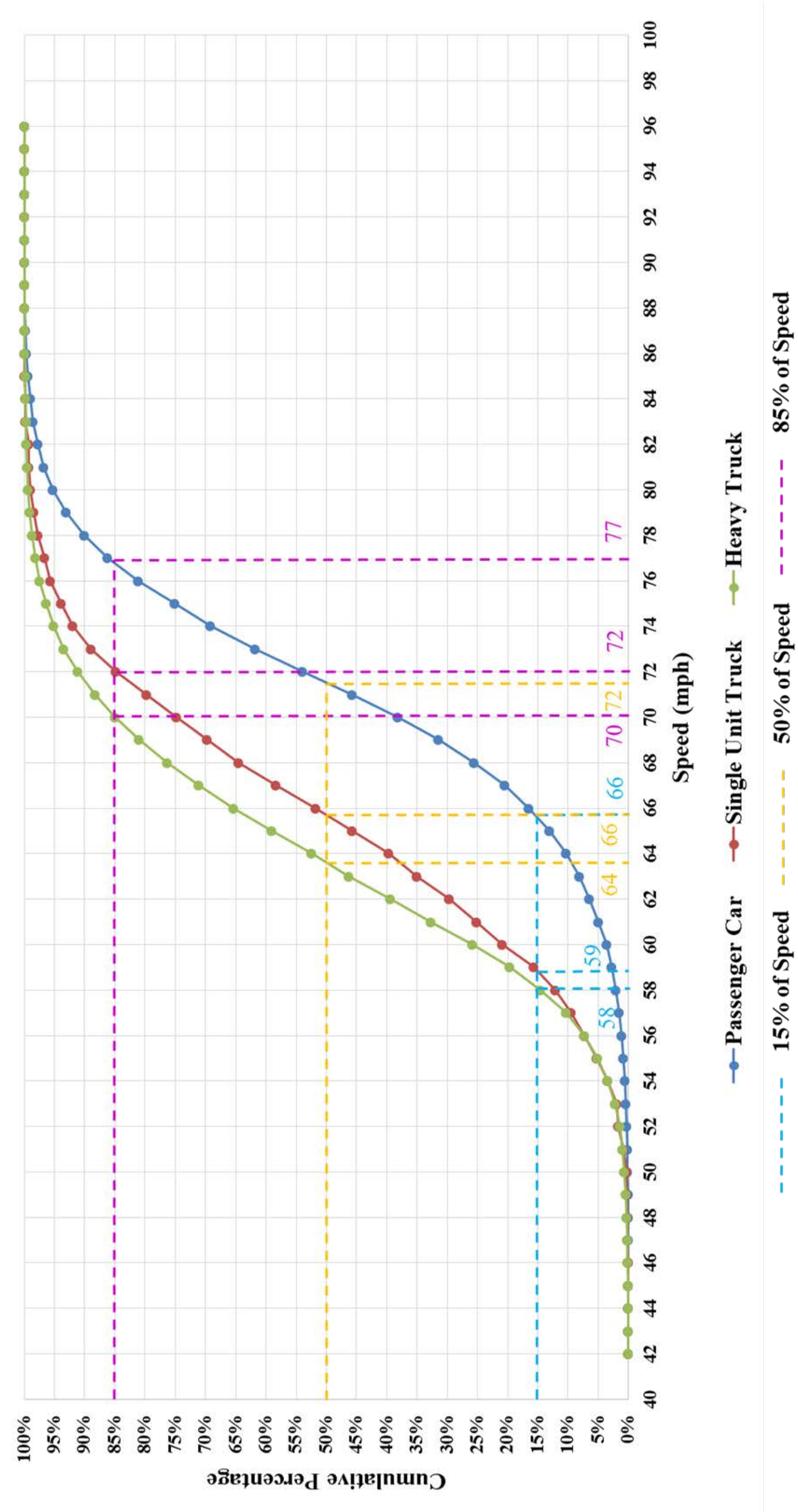

Figure 4.4 Speed distribution for all vehicles

Chapter 5 HCM Analysis

5.1 PCE in HCM 2010

5.1.1 Recommended PCE Values in HCM 2010

In the 2010 HCM, PCEs for basic freeway segments are in two forms. The first is for average conditions across three types of terrain: level, rolling, and mountain. The second is for specific segments of a given length and grade. In both cases, the PCE is provided as a function of the percentage of heavy vehicles. On the I-80 between Lincoln and North Platte, Nebraska, the grades for all data collection sites were no greater than 2% and therefore may be defined as the level terrain type in the HCM. The recommended PCE values for: 1) freeways according to terrain type and 2) on specific upgrades are shown in tables 5.1 and 5.2. It may be seen that for level terrain types, the HCM PCE value for trucks and buses is 1.5. The HCM 2010 recommends a value of 1.5 for specific upgrade segments of: 1) less than two percent, 2) any length, and 3) any truck percentage. For truck percentage higher than 25%, the HCM recommends the PCE value as 25% trucks percentage, since in pervious HCM the PCE is only provided up to 25% truck percentage.

5.1.2 PCE Determination Method in HCM 2010

In the HCM 2010, PCEs for basic freeway segments were determined by the equal-density method using simulated data (Webster and Elefteriadou 1999). The equal-density method is a specific type of the equal-impedance method introduced in chapter 2. In this instance, “density” is specified as the impedance and measurement of the effectiveness of the traffic flow.

To determine PCEs for trucks at a given traffic condition, curves need to be developed for representing density-volume relationships for three different traffic flow types: base flow, (e.g., passenger-car-only flow); mixed flow, (e.g., traffic flow with a given percent of passenger cars and trucks); and subjected flow (e.g., where a certain number of passenger cars in the mixed-traffic are replaced by an equal number of trucks). For example, if the PCE for a traffic flow consists of a volume at 1500 veh/h, with 20% of the truck percentage needs to be determined, then the base flow is 1500 passenger car/h passenger-car-only flow, and the mixed flow has 1200 passenger car/h volume and 300 truck/h volume. As discussed in chapter 2, 5% of the passenger volume is replaced by trucks. In this case, the subjected flow is composed of 1125 passenger cars/h and 325 trucks/h. The PCE is determined based on the base, mixed, and subject vehicle traffic flow producing the same density. The method is illustrated by figure 5.1, and equation 5.1 is used.

$$\boldsymbol{PCE} = \frac{\mathbf{1}}{\Delta \boldsymbol{p}}\left(\frac{\boldsymbol{q_B}}{\boldsymbol{q_S}} - \frac{\boldsymbol{q_B}}{\boldsymbol{q_M}}\right) + \mathbf{1} \qquad (5.1)$$

$\boldsymbol{PCE}$	passenger car equivalents for subject vehicles
$\Delta \boldsymbol{p}$	proportion of subject vehicles adding to the mix and subtracted from the base flow
$\boldsymbol{q_B}$	flow rate at same density for base traffic flow
$\boldsymbol{q_M}$	flow rate at same density for mixed traffic flow
$\boldsymbol{q_S}$	flow rate at same density for subject vehicle traffic flow

The PCE value in the HCM 2010 was determined based on data simulated by FRESIM. Also, the level terrain is defined as: “any combination of grades and horizontal or vertical alignment that permits heavy vehicles to maintain the same speed as passenger cars, and this type of terrain typically contains short grades of no more than 2%" (HCM 2010, p. 11-44). In other words, PCEs at the level terrain are determined based on the assumption that passenger cars and trucks share the same speed distribution. This is also stated in the 2010 HCM.

5.2 Speed-Volume Analysis

5.2.1 Speed-Volume Analysis with Empirical Data

Based on the HCM 2010, there are five steps for speed-volume analysis.

Step 1: Free-flow speed estimation (FFS)

Step 2: Select FFS curve

Step 3: Determine heavy vehicles adjustment factor

Step 4: Determine adjusted demand flow rate

Step 5: Generate plot for speed-volume relationship

In step 1, the free-flow speed is estimated using the following equation in the HCM 2010.

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22TRD^{0.84} \qquad (5.2)$$

FFS	free flow speed of basic freeway segment (mi/h)
f_{LW}	adjustment for lane width (mi)
f_{LC}	adjustment for right-side lateral clearance (mi/h)
TRD	total ramps density (ramps/mi)

For all study sites, the lane width is 12 feet. This is the base condition, which produces no negative effects on the free-flow speed. Therefore, the value of f_{LW} is set as 0. The right-site lateral clearance for all study sites is 6 feet. This is also the base condition, and the value of f_{LC} is set as 0. Total ramp density is defined as the quotient of the number of ramps (on and off in one direction) located between 3 miles upstream and 3 miles downstream of the midpoint of the basic freeway segment under study, and the segment distance. The ramp density is used to estimate the impact of merging and diverging vehicles on the FFS (HCM 2010, p. 11-12). Because the study sites are located in western Nebraska, the ramps are located several miles from one another. There is only one exit and one entrance ramp in a 6 mile segment. The ramp density is 2/6 or 1/3 ramps per mile. Therefore, the free-flow speed for all of the study sites is 74.1 mph, which is close to 75 mph. Therefore, the FFS curve for 75 mph is selected as the basic for the speed-volume analysis.

In step 3, the adjustment factor for heavy vehicles is determined using equation 5.3 (HCM 2010, p. 11-13).

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \quad (5.3)$$

f_{HV} adjustment factor for presence of heavy vehicles in traffic stream
P_T proportion of trucks and buses in traffic stream
P_R proportion of recreation vehicles in traffic stream
E_T passenger car equivalent (PCE) of one truck or bus in traffic stream
E_R passenger car equivalent (PCE) of one recreation vehicle in traffic stream

Because of very low percentage of buses and recreation vehicles, only trucks are considered in the adjusted factor determination of heavy vehicles. The proportion of trucks in the traffic stream is based on the truck percentage at each 15-min interval, and the passenger car equivalent for a truck is set as 1.5, as recommended in the HCM 2010.

The adjustment demand flow rate is determined using equation 5-4 (HCM 2010, p. 11-13).

$$v_P = \frac{V}{PHF \times N \times f_{HV} \times f_p} \tag{5.4}$$

v_P	demand flow rate under equivalent base conditions (pc/h/ln)
V	demand flow rate under prevailing conditions (veh/h)
PHF	peak-hour factor
N	number of lanes in analysis direction
f_{HV}	adjustment factor for presence of heavy vehicles in traffic stream
f_p	adjustment factor for unfamiliar driver populations

The demand volume under the prevailing condition is determined by the flow rate based on a 15-min interval. The adjustment factor for unfamiliar driver populations was set to 1.0 because it was assumed that the driver was familiar with the routes on level terrain. The PHF represents the variation in traffic flow within an hour, and is determined by the following equation.

$$PHF = \frac{V_v}{V_H} \tag{5.5}$$

PHF	peak-hour factor
V_v	Actual demand volume under prevailing conditions (veh/h)
V_H	volume/hourly flow rate based on 15-minute interval with highest volume

The value of the PHF is a function of 15-min volume. For the I-80 test sites, the value ranges from 0.69 to 0.98.

5.2.2 Comparison between Empirical Data and HCM

The estimated flow rate and measured speed for each 15-minute interval are shown in figure 5.2. Also shown in the figure is the FFS curve for 75 mph and the corresponding level of service (LOS). It may be seen that vehicles on the shoulder lane experience a lower speed and a higher density compared to the median lane.

In both figure 5.2 and figure 5.3, the individual data point represents the speed-volume relationship for empirical data in each 15-minite interval. The red curve is the FFS curve for 75 mph, as used in the HCM 2010. In figure 5.2, the "traffic volume" represents the average flow rate per lane per hour, and the "speed" represents the average speed for two lanes in a 15-minute interval. In figure 5.3, the "traffic volume" represents the flow rate per hour for the shoulder and the median lane separately, and the "speed" represents the average speed for the shoulder and the median lane separately, in a 15-minute interval. The area of the LOS, based on the density values recommended in the HCM 2010, is also shown in the figures.

From these two figures, which are based on a PCE of 1.5, the following can be understood.

(a) The hourly traffic volume on I-80 is comparatively low. According to the figures, the average flow rate per lane per hour is less than 1100 veh/h. The flow rate per hour for the shoulder lane is less than 1200 veh/h, and the flow rate per hour for the median lane is less than 1000 veh/h.

(b) The level of service for the traffic flow ranges from level A to B. For all 15-minute-interval traffic flow observations on two lanes, the level of service ranges from level A to B, which is the same as all 15-minute-interval traffic flow observations on the shoulder lane. The level of service for 15-minute-interval traffic flow observations on the median lane is level A, and a small portion of it is level B. Therefore, based on density, the level of service for I-80 is high, and the level of service for the median lane is higher than the shoulder lane.

(c) In general, the observed speed is lower than the predicted curve. For 85% of all 15-minute intervals, the actual speed of traffic flow is 0 to 15 mph lower than the speed stated in the FFS curve for 75 mph at the corresponding range of the traffic volume. For observations on the median lane, the actual speed is 0 to 10 mph lower than the speed stated in the FFS curve, which ranges from 65 mph to 75 mph. For observations on the shoulder lane, the actual speed is 0 to 15 mph lower than the speed stated in the FFS curve, which ranges from 60 mph to 75 mph. It may be seen that the average speed of vehicles on the shoulder lane is significantly lower than that on the median lane. Assuming that the 75 mph FFS curve is correct, the empirical speeds correspond to the LOS C or D.

Based on a standard HCM analysis, I-80 has good traffic operation conditions. However, the low predicted operating speed indicates that the HCM analysis might not be appropriate for I-

80. Anecdotally, vehicles are frequently observed operating in platoons. Therefore, it is hypothesized that the lower speed may be attributed to the existence of platoons, and the platoons are affecting the speed-density relationship assumed in the HCM. If so, the PCE value recommended in the HCM might be too low.

5.3 Concluding Remarks

In this chapter, the recommended value for the PCE and the 2010 HCM traffic analysis method are first introduced. In the HCM 2010, for basic freeway segments at level terrain, the PCEs are 1.5 for all grade percentages, lengths, and truck percentages, and the value is determined by the equal-density method based on the simulation data from FRESIM. PCEs at level terrain are determined under the assumption that passenger cars and trucks share the same speed distribution. The speed-volume relationship based on the empirical data is determined, analyzed, and compared to the FFS curve provided in the HCM 2010. Results of the speed-volume analysis based on the empirical data show that for I-80 between Lincoln and North Platte, Nebraska, the level of service is at level A or B. However, the operating speeds are lower than those predicted by the HCM. These speeds correspond to a LOS at C or D. It is hypothesized that a platoon or a difference in speed between the passenger car and trucks results, or both. If this is true, the HCM PCE values may be too low.

Table 5.1 PCE value in HCM 2010 for freeway by type of terrain

Vehicle	**Level**	**Rolling**	**Mountainous**
Trucks and buses, E_T	1.5	2.5	4.5

Table 5.2 PCE value in HCM 2010 for freeway at level terrain by proportion of trucks

Upgrade (%)	Length (mi)	2%	4%	5%	6%	8%	10%	15%	20%	≥25%
≤ 2	All	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
>2–3	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.50–0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.75–1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>1.00–1.50	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>1.50	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
>3–4	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50–0.75	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	>0.75–1.00	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	>1.00–1.50	3.5	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
	>1.50	4.0	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
>4–5	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.50–0.75	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5
	>0.75–1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0
	>1.00	5.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0
>5–6	0.00–0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.30	4.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.30–0.50	4.5	4.0	3.5	3.0	2.5	2.5	2.5	2.5	2.5
	>0.50–0.75	5.0	4.5	4.0	3.5	3.0	3.0	3.0	3.0	3.0

	>0.75–1.00	5.5	5.0	4.5	4.0	3.0	3.0	3.0	3.0	3.0
	>1.00	6.0	5.0	5.0	4.5	3.5	3.5	3.5	3.5	3.5
>6	0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	>0.25–0.30	4.5	4.0	3.5	3.5	3.5	3.0	2.5	2.5	2.5
	>0.30–0.50	5.0	4.5	4.0	4.0	3.5	3.0	2.5	2.5	2.5
	>0.50–0.75	5.5	5.0	4.5	4.5	4.0	3.5	3.0	3.0	3.0
	>0.75–1.00	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	3.5
	>1.00	7.0	6.0	5.5	5.5	5.0	4.5	4.0	4.0	4.0

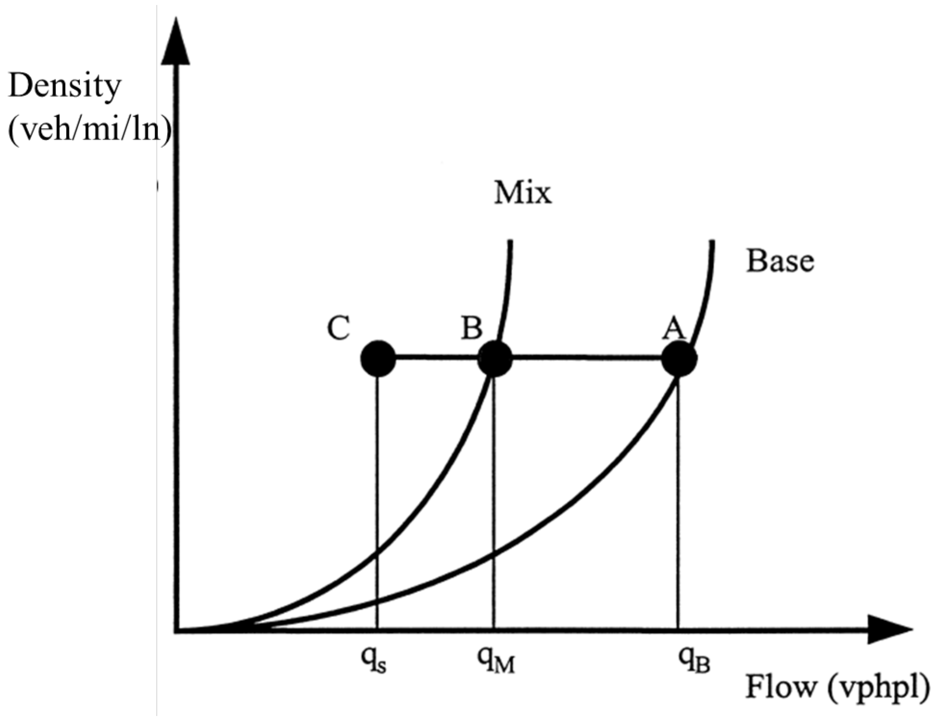

Figure 5.1 Method of equal-density PCE calculation

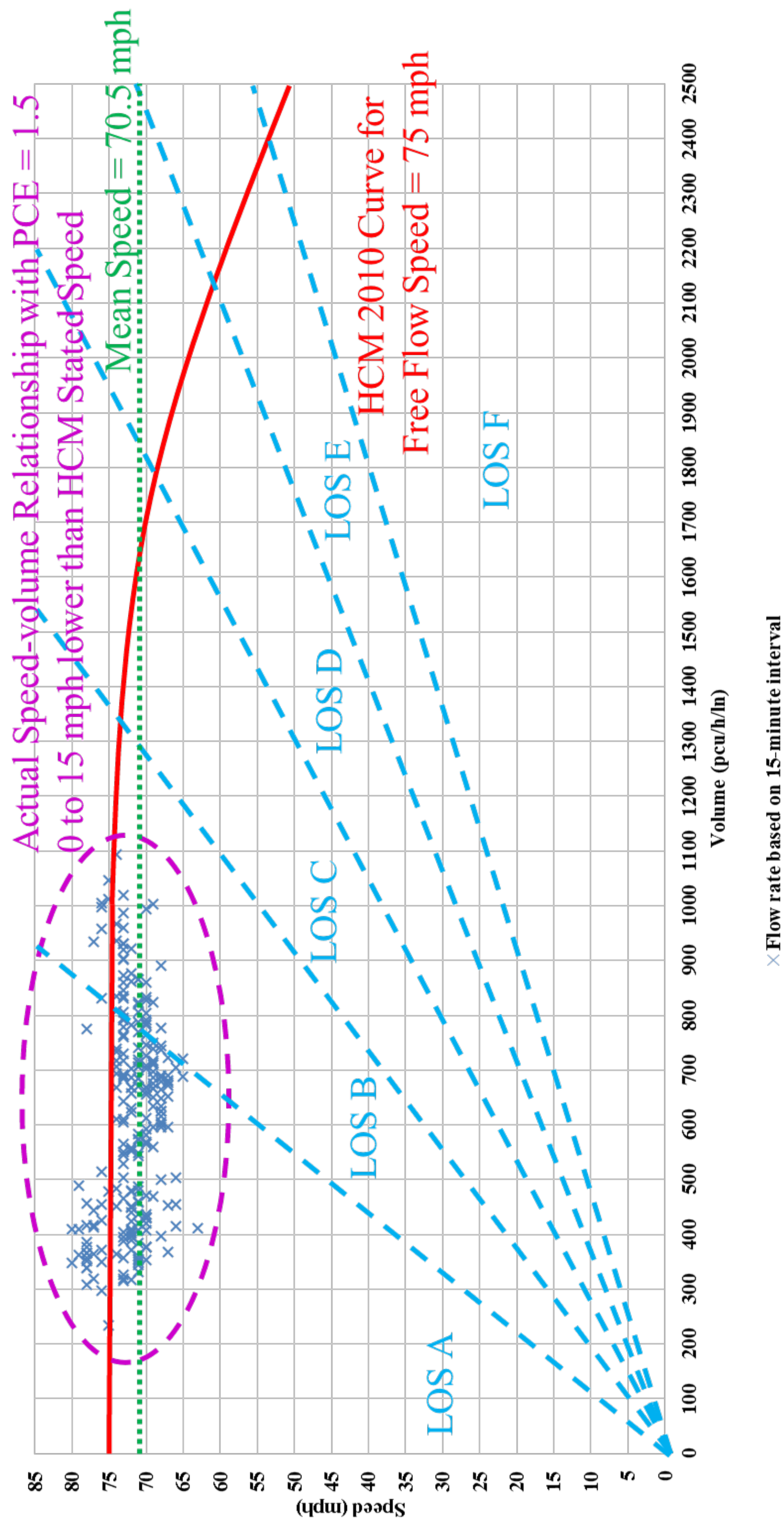

Figure 5.2 Results of speed-volume analysis for empirical data

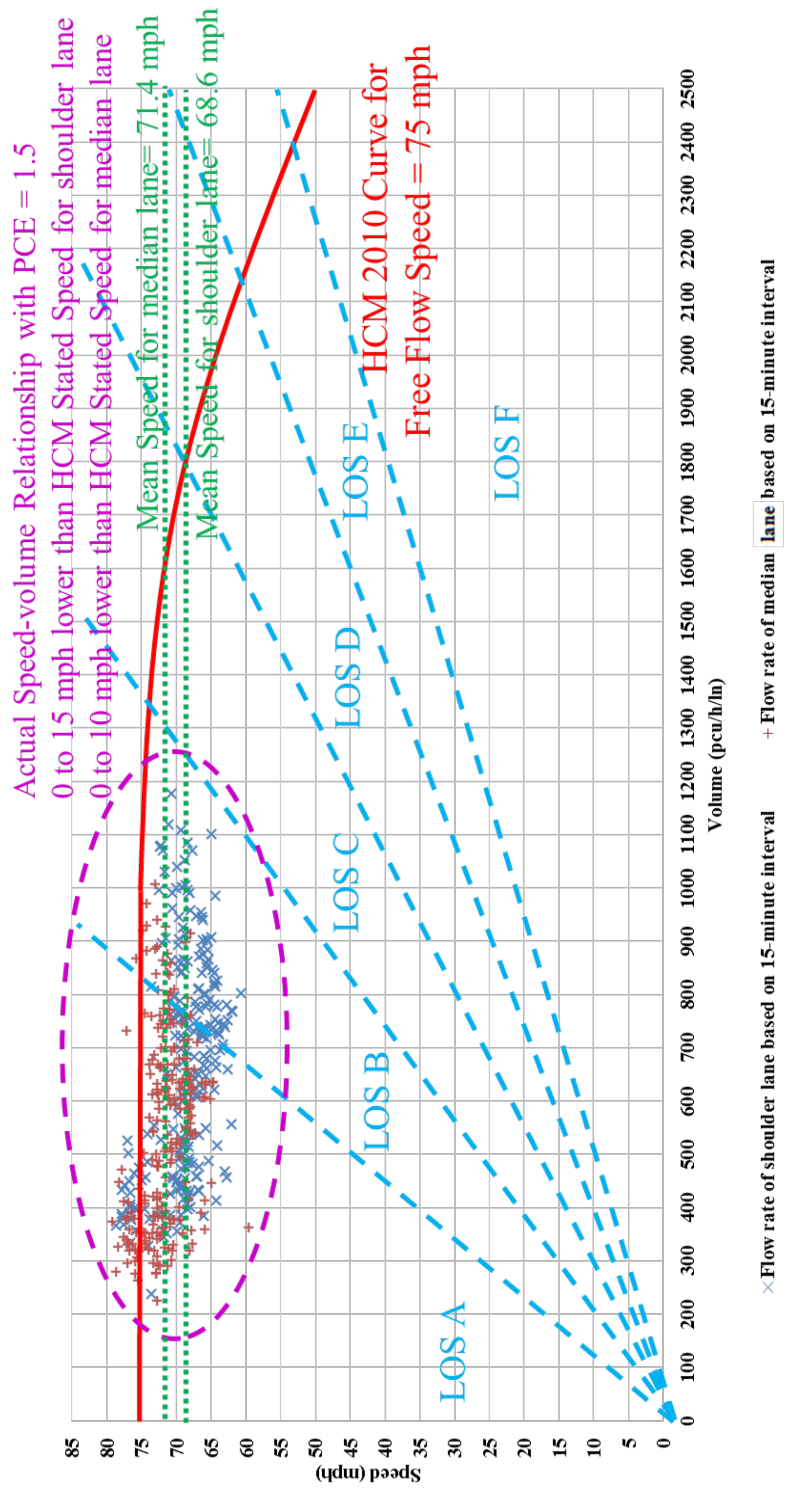

Figure 5.3 Results of speed-volume analysis for empirical data (shoulder and median lane are shown separately)

Chapter 6 Platoon Analysis

6.1 Platoon Identification

6.1.1 Platoon Definition

In general, platooning is caused by fast vehicles that catch up with slower vehicles, which are unable to pass (Yagar 1984). Vehicles that do not catch up with other vehicles, or vehicles that are not impeding other vehicles, are defined as “free vehicles.” These vehicles are not in the platoon. There is no universally accepted standard for identifying a platoon, and studies that investigated car-following interactions aimed at identifying free vehicles are limited. On freeways, highways, and urban roads, one accepted definition of a free vehicle is that its speed is not influenced by the speed of the vehicle traveling ahead of it (Karjala 2002; Al-Kaisy 2010). This is usually identified by headways between the leading and following vehicles. In order to be considered a free vehicle, the headways should be greater than a specific threshold (Hansen 2007; Ali 2007). In this research, a platoon is defined as a group of vehicles traveling on either the median or the shoulder lane in the same direction, which influence the speed of one another.

In this research, a platoon is identified based on the leading headway and lagging headway. The leading headway represents the time between the front bumper of the leading vehicle passing a specific location and the front bumper of the following vehicle passing the same location. Similarly, the lagging headway represents the time between the rear bumper of the leading vehicle passing a specific location and the rear bumper of the following vehicle passing the same location. The thresholds for platoon identification are defined as the “critical leading headway” and the “critical lagging headway”, respectively. Vehicles on all lanes in one direction with leading headways less than or equal to the critical leading headway, or with lagging headways less than or equal to the critical lagging headway, are considered to belong to the same platoon. In contrast, vehicles with both leading and lagging headways greater than the corresponding critical headways are considered independent (e.g., not in a platoon). All vehicles identified in platoons are defined as “in-platoon vehicles,” and all vehicles identified not in platoons are defined as “free-flow vehicles.” The platoon is defined by the following equation. This concept is illustrated by figure 6.1. In this example, the critical leading headway is set as 3s, and the critical lagging headway is set as 4s.

$$p_i = \begin{cases} 1 \left(F_i - F_{i+1} \leq C_{leading} \; and \; R_i - R_{i+1} \leq C_{lagging}\right) \\ 1 \left(F_i - F_{i+1} \leq C_{leading} \; and \; R_i - R_{i+1} > C_{lagging}\right) \\ 1 \left(F_i - F_{i+1} > C_{leading} \; and \; R_i - R_{i+1} \leq C_{lagging}\right) \\ 0 \left(F_i - F_{i+1} > C_{leading} \; and \; R_i - R_{i+1} > C_{lagging}\right) \end{cases} \quad (6.1)$$

p_i	indicator for vehicle whether in platoon or not, 1-in platoon, 0-not in platoon
i	order of vehicle, $i + 1$ means its following vehicle
F_i	time front bumper of leading vehicle *i* pass specific location
F_{i+1}	time front bumper of following vehicle $i + 1$ pass specific location
$C_{leading}$	critical leading headway
R_i	time rear bumper of leading vehicle *i* pass specific location
R_{i+1}	time rear bumper of following vehicle $i + 1$ pass specific location
$C_{lagging}$	critical lagging headway

It may be seen that there are two platoons. Each platoon has one or two platoon leaders that influence the speed of the following vehicles. For platoons occurring on two lanes, both the first vehicle on the shoulder lane and the first vehicle on the median lane are regarded as the "platoon leaders." For platoon 1, the leaders are A and B, and for platoon 2 the leaders are F and G in figure 6.1. Note that for platoons occurring on one lane, only the first vehicle in the platoon is regarded as the "platoon leader." All of the vehicles in the platoon except for the leaders are, by definition, "platoon followers" (e.g., vehicle except A, B, F, and G in figure 6.1).

6.1.2 Critical Headway Determination

In this research, the critical headway is considered not only different between the leading and lagging headways, but also affected by the classification of the leading and lagging vehicles. There are eight critical headway classifications in this report: four related to leading headways and four related to lagging headways:

1) car following car, leading headway (cc-leading);

2) car following truck, leading headway (ct-leading);

3) truck following car, leading headway (tc-leading);

4) truck following truck, leading headway (tt-leading);

5) car following car, lagging headway (cc-lagging);

6) car following truck, lagging headway (ct-lagging);

7) truck following car, lagging headway (tc-lagging); and

8) truck following truck, lagging headway (tt-lagging).

The critical headway is determined based on the following standard.

1) The speed of the vehicles with headways no greater than the critical headway is lower

than the speed of the vehicles with headways greater than the critical headway.

2) The vehicles with headways no greater than the critical headway show a high linear relationship between the speed and headway, while vehicles with headways greater than critical headway show a low linear relationship between the speed and headway.

Table 6.1 shows the critical headway for each of the eight types. Note that the average headway is 5.25s, which is relatively close to 6 seconds predicted by Al-Kaisy (Al-Kaisy 2010). A sensitivity analysis of the headway and speed is provided at the end of the chapter.

6.1.3 Frequency and Percentage of In-Platoon and Free-Flow Vehicles

Based on the critical leading and lagging headways in the table 6.1, it was found that for the 48,561 passenger cars and trucks observed, 42,308 vehicles (87.1% of all vehicles) were identified as belonging to a platoon, and 6,253 vehicles (12.9% of all vehicles) were identified as free-flow vehicles. The frequency and percentage of in-platoon and free-flow vehicles are shown in figure 6.2 and 6.3, respectively. It is hypothesized that platoon affects the speed of vehicles on I-80 and that the platoon occurs because of the different free-flow speeds of passenger cars and trucks.

6.1.4 Platoon and Vehicle Type

In this research, platoons are divided into eight types, and these are summarized in table 6.2. The frequency and percentage of different platoon types are shown in figure 6.4 and 6.5, respectively. The results are detailed below.

1) Nearly 70% of platoons are classified into Type I and Type II platoons, which are led

by two cars, or one truck on a shoulder and one car on a median.

2) The number of two-lane platoons (e.g., Type I, II, III, and IV) is 30% higher than the number of one-lane platoons.

3) One-lane platoons occur more frequently on the shoulder lane than the median lane (e.g., the number of one-lane platoons on the shoulder lane is 17 times that of a median lane); and

4) For two-lane platoons with one car platoon leader as and one truck platoon leader, the car platoon leader is more likely to be in the median lane (e.g., the number of car platoon leaders on the median lane is 12 times that of the shoulder lane), and the truck platoon leader is more likely to be in the shoulder lane (e.g., the number of truck platoon leaders on the shoulder lane is 12 times that of the median lane).

The vehicles were grouped into 4 types according to two vehicle classification (e.g., passenger cars and trucks) and lane type (e.g., shoulder lane and median lane), as summarized in table 6.3. The frequency and percentage of the four vehicle-type lane combinations are shown in figures 6.6 and 6.7, respectively. It should be noted that the vehicles also have classifications of "in-platoon vehicles" and "free-flow vehicles" that are not shown. For passenger cars, the number of vehicles on the median lane is 13.8% higher than that on the shoulder lane. For trucks, the number of vehicles on the shoulder lane is 4.26 times as high as that on the median lane. Nearly 95% of all of the vehicles are classified into type A, B, and C. Very few vehicles are classified into type D, indicating that very few trucks operate on the median lane.

6.2 Analysis for Impeded and Non-Impeded Vehicles

6.2.1 Definition of Impeded and Non-Impeded Vehicles

Based on platoon identification, the vehicles were classified into three groups according to whether: 1) the vehicle was impeding other vehicles; 2) the vehicle was impeded by other vehicles; or 3) the vehicle was neither impeding nor being impeded upon (e.g., free-flow vehicles). In this research, all platoon followers are defined as “impeded vehicles,” under the assumption that the operating speed is constrained by the leading vehicles of the platoon. All platoon leaders are defined as “impeders,” on the assumption that the following vehicles adjust their operating speed because of the presence of the “impeders.” All free-flow vehicles are defined as “non-impeded vehicles,” because their operating speeds are not affected by impeding or impeded vehicles. The impeded vehicles are also divided into two groups according to their corresponding platoon leader. A passenger-car-leading-impeded vehicle is defined as an impeded vehicle that has a passenger car as the platoon leader in its lane. A truck-leading-impeded vehicle is defined as an impeded vehicle with a truck as the platoon leader on its lane. For example, for the type III platoon (e.g,. car as leader on shoulder lane, truck as leader on median lane), the impeded vehicles on the shoulder lane are classified as “car-leading-impeded vehicles,” while the impeded vehicles on the median lane are classified as “truck-leading-impeded vehicles.”

6.2.2 Frequency and Percentage of Impeder, Impeded, and Non-Impeded Vehicles

The frequency and percentage of the impeder, impeded, and non-impeded vehicles are shown in figures 6.8 and 6.9, respectively. These figures show that 51% of vehicles are classified as impeded vehicles, 36% of vehicles are classified as impeders, and approximately 13% of vehicles are classified as non-impeded vehicles. The relatively high number of vehicles classified as impeders indicates there are a high number of small platoons. This will be analyzed later in this chapter.

6.2.3 Speed Distribution for Impeded and Non-Impeded Vehicles

The speed distributions for impeded and non-impeded passenger cars, single-unit trucks, and heavy trucks are shown in figure 6.10. The difference in the average speeds between impeded and non-impeded vehicles for passenger cars, single-unit trucks, and heavy trucks were also analyzed using a t-test, and the results are shown in table 6.4. It was found that the average speeds for cars, single-unit trucks, and heavy trucks that are classified as impeded vehicles are 7.1%, 6.0%, and 4.5% lower than non-impeded vehicles, and this result is statistically significant at the 95% confidence level. Note that for non-impeded vehicles, the average speed of passenger cars is 9.5% lower than trucks, and this difference is statistically significant at the 95% confidence level. The results indicate that the platoon causes travel delay to impeded vehicles rather than non-impeded vehicles. It was also found that even if the single-unit and heavy trucks are classified as non-impeded vehicles, their speeds (e.g., with an average speed 68.1 mph) are still lower than the passenger cars that are classified as impeded vehicles (e.g., with an average speed 71.5 mph).

6.2.4 Additional Analysis for Impeded and Non-Impeded Vehicles

The relationships between the traffic volume and the amount of impeded vehicles, the percentage of impeded vehicles, and the percentage of time impeding are separately analyzed. Figures 4.2 and 4.3 show x-y graphics of the traffic volume and the truck percentage as a function of distance from the west to the east. It may be seen that a negative correlation between the traffic volume and truck percentage exists because the traffic volume increases as the truck percentage decreases. In order to account for this correlation, the empirical data is divided into six groups based on the traffic volume and truck percentage.

1) Low volume (<=700 veh/h), medium truck percentage (>25%, <=35%)

2) Low volume (<=700 veh/h), high truck percentage (>35%)

3) Medium volume (>700 veh/h, <=1100 veh/h), low truck percentage (<=25%)

4) Medium volume (>700 veh/h, <=1100 veh/h), medium truck percentage (>25%, <=35%)

5) Medium volume (> 700 veh/h, <=1100 veh/h), high truck percentage (>35%)

6) High volume (>1100 veh/h), low truck percentage (<25%)

6.2.4.1 Analysis for Amount of Impeded Vehicles

The relationship between traffic volume and the number of impeded vehicles is shown in figure 6.11. Following the HCM practice, the hourly traffic volume (veh/h) and the amount of impeded vehicles (veh/h) are determined based on the 15-minute-interval observation and converted to an hourly count. The diagonal in the figure represents the upper bound situation where all vehicles are impeded. Figure 6.11 shows that, for all combinations of traffic volume and truck percentage, the amount of impeded vehicles increases with the traffic volume. There are 240 estimates in figure 6.11 (e.g., 60 hour 15-minute intervals). The amount of impeded vehicles ranges from 100 veh/h to 1100 veh/h.

6.2.4.2 Analysis of Percentage of Impeded Vehicles

The relationship between the traffic volume and percentage of impeded vehicles is shown in figure 6.12. The hourly traffic volume (veh/h) and the percentage of impeded vehicles are determined based on the 15-minute interval observation. For all of the combinations of traffic volume and truck percentage, the percentage of impeded vehicle increases with traffic volume, but at a slightly decreased rate. The percentage of impeded vehicles ranges from 20% to 75%.

6.2.4.3 Analysis for Percentage of Time Impeding

In order to estimate the time a vehicle is being impeded in a platoon, the Percentage of Time Impeding (PTI) was created. The PTI is the quotient of the time duration of vehicles being impeded and the interval lasting time, as shown in equation 6-2.

$$PTI = \frac{T_{impeded}}{T_{interval}} \tag{6-2}$$

PTI	percentage of time impeding
$T_{impeded}$	the time duration of vehicles being impeded
$T_{interval}$	the interval lasting time

The duration for vehicles being impeded is defined as the sum of the duration of the detectors being occupied by the impeded vehicles, and the gaps between the impeded vehicles and their leading vehicles, as shown in equation 6-3.

$$T_{impeded} = \sum_{i=1}^{n} T_{detectori} + \sum_{i=1}^{n} T_{gapi} \quad (6\text{-}3)$$

$T_{impeded}$	the time duration of vehicles being impeded
$T_{detectori}$	the duration of detector being occupied by the *i*th impeded vehicle
T_{gapi}	the gap between the *i*th impeded vehicle and the leading vehicle
i	the *i*th impeded vehicle
n	the number of impeded-vehicles

The hourly traffic volume (veh/h) and the percentage of time impeding are determined based on the 15-minute-interval observation. The relationship between the PTI and the traffic volume is shown in figure 6.13. It may be seen that for all of the combinations of traffic volume and truck percentage, the PTI increases with the traffic volume. The PTI ranges from 5% to 45%.

6.3 Platoon Characteristics

6.3.1 Overview of Platoon Characteristics

This section aims at showing effects of platoon types on different platoon characteristics. Three categories of platoon characteristics were evaluated for traffic flow:

1) Speed-related platoon characteristics, including the speed of impeded and non-impeded vehicles, the difference in speed of impeded and non-impeded vehicles, and the ratio of impeded vehicle speed to free flow speed;

2) Number and density of impeded vehicles in platoon;

3) Characteristics related to platoon existence, including platoon existence time, platoon existence distance, and platoon-caused-delay experienced by passenger car with FFS=75 mph.

6.3.2 Speed-related Platoon Characteristics

1. Speed of impeded and non-impeded vehicles (IVS/FFS)

Figure 6.14 shows a box plot of observed speed for ten categories. The first eight are for vehicles that are classified or belonging to a platoon (e.g. impeded vehicles). The eight categories correspond to the classification scheme shown in Table 6.2 and are based on the platoon leader vehicle type and lane position. Figure 6.15 shows a box plot of passenger car speed, following the same classification as Figure 6.14. Figure 6.16 shows a box plot of truck speed, following the same classification as Figure 6.14 and Figure 6.15. These box plots show that:

(a) Speeds of impeded vehicles (IVS) are significantly lower than the speeds of the non-impeded vehicles (free flow speed, FFS). The median of impeded vehicle speed ranges from 64 mph to 71 mph, and the median of non-impeded vehicle speeds range from 73 to 75 mph. The difference in mean speed between impeded and non-impeded passenger cars is higher than that for trucks, indicating passenger cars experiencing more speed reduction than trucks;

(b) Speeds of impeded vehicles in two-lane platoons are significantly lower than in one-leader platoon. For all vehicles, median of impeded vehicle speed in two-lane platoon ranges from 64 mph to 70 mph, and median of impeded vehicle speed in one-lane platoon ranges from 70 to 71 mph. The difference in mean speed between passenger cars in two-lane and in one-lane platoons is higher than that for trucks, indicating passenger cars experiencing more speed reduction than trucks if caught in two-lane platoons;

(c) Speeds of impeded vehicles in platoons with two trucks as leaders are significantly lower than in platoon with two cars as leaders, which indicates truck-leading-platoon may cause more delay compared with car-leading-platoon.

The results of t-test for these comparisons are shown in Table 6.5.

2. Difference in speed of impeded and non-impeded vehicles (DiffIVS-FFS)

This indicator measures how much the speed of impeded vehicle lower than the mean speed of non-impeded vehicles in corresponding 15-minute interval as the following equation:

$$DiffIVS - FFS = IVS - FFS \tag{6-4}$$

$DiffIVS - FFS$	- difference in speed of impeded vehicle and non-impeded vehicles
IVS	- speed of impeded vehicle
FFS	- the mean speed of non-impeded vehicles in corresponding 15-minute interval

The low value indicates the amount of speed reduction is high. For here, the difference between speed of impeded vehicles and the mean speed of non-impeded vehicles in corresponding 15-minute interval for vehicles in each platoon type is analyzed. The box plot for distributions of DiffIVS-FFS for each platoon type is shown in Figure 6.17. The figure shows that impeded vehicles in two-lane platoons experience more speed reduction than impeded vehicles in one-lane platoons, and impeded vehicles in platoons led by two trucks experience highest speed reduction.

3. Ratio of impeded vehicle speed to non-impeded vehicle speed (IVS-FFS%)

This indicator measures percentage of speed reduction for impeded vehicles compared with the mean speed of non-impeded vehicles in corresponding 15-minute interval, as the following equation:

$$IVS - FFS\% = \frac{IVS}{FFS} \times 100\% \tag{6-5}$$

$IVS - FFS\%$	- ratio of impeded vehicle speed to the mean speed of non-impeded vehicles
IVS	- speed of impeded vehicle
FFS	- the mean speed of non-impeded vehicles in corresponding 15-minute interval

Similar to DiffIVS-FFS, the low value indicates the percentage of speed reduction is high. The box plot for distributions of IVS-FFS% for each platoon type is shown in Figure 6.18. The figure shows that IVS-FFS% for impeded vehicles in two-leader platoons is lower than that in one-leader platoons, and impeded vehicles in platoons led by two trucks experience highest percentage of speed reduction.

6.3.3 Number and Density of Impeded Vehicles in Platoon

The number of impeded vehicles (NIV) measures the length of platoon. The high value in the number of impeded vehicles indicates the platoon length is high. The density of impeded vehicles (DIV) measures the degree of congestion for impeded vehicles in platoons. The high value in the density of impeded vehicles represents high degree of congestion and low level of service. The density of impeded vehicles is defined as the number of impeded vehicles in a directional traffic flow over 1 mile per lane, and estimated by the following equation:

$$DIV = \frac{NIV}{\overline{IVS} \times T_{impeded} \times N} \tag{6-6}$$

DIV	- density of impeded vehicles
NIV	- number of impeded vehicles
$\overline{IVS}$	- average speed of impeded vehicles
$T_{impeded}$	- the time duration of vehicles being impeded in one platoon

N - number of lanes

The time duration of vehicles being impeded in one platoon is the sum of the duration of detectors being occupied by impeded vehicles in one platoon, and the gaps between impeded vehicles and their leading vehicles in one platoon. Equation 6-3 is used here.

The average number and density of impeded vehicle for different platoon types are shown in Figure 6.19 and 6.20 respectively. The figure shows that the average number of impeded vehicle for two-lane platoons is higher than one-lane platoons with highest value occurring in Type IV platoon (7.2), indicating the Type IV platoon has the highest length. The average density of impeded vehicles for two-lane platoons is higher than one-lane platoons with highest value occurring in Type IV platoon (30 veh/mile/ln), indicating that vehicles experience the most severe congestion if impeded in platoon led by two trucks.

6.3.4 Characteristics related to platoon existence

In this section, the platoon existence time, platoon existence distance, and platoon-caused-delay experienced by passenger car with free flow speed 75 mph are analyzed. Platoon existence time and distance measures how long and for what distance vehicles are actually impeded in a platoon and affected by it, considering the formation and dispersion of platoons, not just the length and impeding time of platoon shown in video recordings from fixed location. The existence time and distance of two-lane platoons can be estimated if there is difference in speed between leader vehicles.

In this research, it is assumed that the two-lane platoon is formed due to the faster impeded vehicles tending to overtake its leading slower impeded vehicles on the same lane; then, the faster impeded vehicles change its lane during overtaking and the two-lane platoon is formed. A two-lane platoon can be separated into two parts, the part tending to overtake its leading vehicles with faster average speed is faster platoon, led by faster leader and followed by faster impeded vehicles. Similarly, the part being overtaken with slower average speed is slower platoon, led by slower leader and followed by slower impeded vehicles. The absolute value of difference in average speed between faster platoon and slower platoon is defined as "platoon speed difference". The two-lane platoon starts when the faster leader starts overtaking the last slower impeded vehicle, and ends when the last faster impeded vehicle ends overtaking the slower leader. At the beginning of two-lane platoon existence, all vehicles in faster platoon fall behind all vehicles in slower platoon; at the end of two-lane platoon existence, all vehicles in faster platoon pass all vehicles in slower platoon.

The platoon existence time (*t*) is defined as the time duration between the beginning of platoon existence and the end of the platoon existence. The platoon existence distance (*s*) is defined as the travel distance for faster leader during platoon existence time. The platoon delay (*pd*) is defined as delay experienced by impeded vehicle in platoon, which is equal to the difference between the actual travel time when vehicles impeded in platoon and the travel time when vehicles travel with free flow speed. Illustration for definitions above is shown in Figure 6.21. According to this figure, the platoon existence time, distance and platoon delay is determined by the following equations:

$$\begin{cases} t = \left(l_f + l_s + Gap_1 + Gap_2\right)/\left(v_f - v_s\right) \\ s = v_f * t \\ pd = s * (1/v - 1/FFS) \end{cases} \tag{6-7}$$

t	- platoon existence time
s	- platoon existence distance
pd	- platoon delay experienced by individual impeded vehicle
l_f	- length of faster platoon
l_s	- length of slower platoon
v_f	- average speed of vehicles in faster platoon
v_s	- average speed of vehicles in slower platoon
Gap_1	- safety distance between rear bumper of last slower impeded vehicle and front bumper of faster leader
Gap_2	- safety distance between rear bumper of last faster impeded vehicle and front bumper of slower leader
v	- speed of individual impeded vehicle
FFS	- free flow speed of individual impeded vehicle

Platoon existence time and distance vary with platoon speed difference and length of faster and slower platoon. Effects of platoon speed difference are theoretically analyzed under two assumed conditions, with only one car in faster platoon and slower platoon (e.g. Type I platoon), and only one truck in faster platoon and slower platoon (e.g. Type IV platoon). The two conditions can also be described as a faster car overtaking a slower car, and a faster truck overtaking a slower truck. Therefore, the time and distance for one car overtaking another car or one truck overtaking another truck represents the platoon existence time and distance here respectively. Other assumptions include a) speed of slower car and truck are set at 70 mph and 67 mph, respectively; b) speed of faster car and truck are set as one to four mph higher than the slower vehicle; c) length of car and truck are set as 8ft and 35ft, respectively; d) and the two gaps are set to 328ft, which is widely used in confirming inter-vehicle distance on freeways. The delays of impeded passenger cars caused by these two-lane platoons are also analyzed. The free flow speed of impeded passenger cars is assumed as 75 mph. Figures for conditions of theoretical analysis are shown in appendix. The results of theoretical analysis are shown in the Table 6.6 and the figures are shown in appendix. The results of platoon existence time, distance and platoon delay for passenger cars with 75 mph free flow speed based on empirical data are shown in Table 6.7, Figure 6.22, and Figure 6.23.

As would be expected, the theoretical analysis results show that platoon existence time, distance, and platoon delay decreases with the increase in platoon speed difference. Delay caused by Type I platoons are 55% lower than that of Type IV platoons, which means platoons led by two trucks affect impeded vehicles longer and cause more delays than platoons led by two cars. Empirical analysis results show that lowest average existence time, distance, and delay occur in platoons led by two cars (Type I platoon), and are highest for platoons led by two trucks (Type IV platoon). Platoons led by a truck in the median lane and a car in the shoulder lane (Type III platoon) had the longer existence time, distance, and delays than those led by a truck in the shoulder lane and a car in the median lane (Type II platoon). Overall, if vehicles are impeded in platoons led by two trucks, the vehicles will be most severely affected by platoons with longest time and distance, and experience the highest platoon delay.

6.4 Concluding Remarks

This chapter defines the platoon based on speed and identifies it based on headway. The platoon is defined as a group of vehicles travel on either the median or shoulder lane in the same direction that influence the speed of one another, and identified by both critical leading and lagging headway. The critical headways vary among the vehicle classification of leading and lagging vehicles, determined by the criterions that vehicles with headways no greater than critical headway show lower speed and higher linear relationship between speed and headway than vehicles with headways greater than critical headways. Results of platoon identification show that 87.1% of vehicles are impeded in platoon and only 12.9% of vehicles are identified as free flow vehicles. Platoons are divided into eight types according to vehicle classifications of platoon leaders and lane type, and vehicles are grouped into 4 types according to vehicle classifications and lane type. The vehicles are classified into three groups, which are impeded vehicles, impeders and non-impeded vehicles. 51% of vehicles are classified into impeded-vehicles, and only approximately 13% of vehicles are classified into non-impeded vehicles. The average speeds for both cars and trucks as impeded vehicles are significantly lower than as non-impeded vehicles, indicating platoon cause travel time increase and delay for vehicles. It is found that, amounts and percentage of impeded vehicles, as well as percentage of time impeding, increase with traffic volume. Also, three categories of platoon characteristics are evaluated to analyze the effects of platoon types: 1) Speed-related platoon characteristics, including the speed of impeded and non-impeded vehicles, the difference in speed of impeded and non-impeded vehicles, and the ratio of impeded vehicle speed to free flow speed; 2) Number and density of impeded vehicles in platoon; 3) Characteristics related to platoon existence, including platoon existence time, platoon existence distance, and platoon-caused-delay experienced by passenger car with 75 mph free flow speed. Results of indicators show that on average vehicles impeded in platoons led by two trucks (Type IV platoon) experience the highest speed reduction, degree of congestion, and platoon delay; also, platoons led by two trucks have the longest platoon length, existence time and distance. Therefore, if vehicles are impeded in platoons led by two trucks, the vehicles are most severely affected by platoons.

Table 6.1 Results of critical headway determination

Headway Type	**Critical Headways (s)**	**Headway Type**	**Critical Headways (s)**
cc leading	3.0	cc lagging	3.0
ct leading	8.0	ct lagging	7.0
tc leading	6.0	tc lagging	6.0
tt leading	5.0	tt lagging	4.0

Table 6.2 Summary of platoon type

Platoon Type	**Lanes**	**Leader on Shoulder Lane**	**Leader on Median Lane**
Type I	Two lanes	Passenger car	Passenger car
Type II	Two lanes	Truck	Passenger car
Type III	Two lanes	Passenger car	Truck
Type IV	Two lanes	Truck	Truck
Type V	One lane	Passenger car	--
Type VI	One lane	--	Passenger car
Type VII	One lane	Truck	--
Type VIII	One lane	--	Truck

Table 6.3 Summary of vehicle type

Vehicle Type	Vehicle Classification	Lane
Type A	Passenger car	Shoulder lane
Type B	Passenger car	Median lane
Type C	Truck	Shoulder lane
Type D	Truck	Median lane

Table 6.4 Results of T-test for comparisons between impeded and non-impeded vehicle speed

Comparison	Difference (Impeded – Non-impeded) (mph)	Value of T-test	P-value
Speed of Impeded v.s. Non-impeded Passenger Car	-5.2	-47.1 (Difference < 0)	< 0.05
Speed of Impeded v.s. Non-impeded Single-unit Truck	-4.8	-6.47 (Difference < 0)	< 0.05
Speed of Impeded v.s. Non-impeded Heavy Truck	-3.3	-17.91 (Difference < 0)	< 0.05

Table 6.5 Results of T-test for comparisons for speed of impeded vehicles

Comparison	Difference (mph)	Value of T-test	P-value
Speed for impeded v.s. non-impeded vehicle	-5.1	-39.7 (Difference < 0)	< 0.05
Speed for impeded vehicle in two-lane platoon v.s. one-lane platoon	-3.5	-12.61 (Difference < 0)	< 0.05
Speed for impeded vehicle: Platoon led by two trucks versus platoon led by two cars	-6.4	-26.30 (difference < 0)	<0.05

Table 6.6 Theoretical analysis for effects of platoon speed difference on platoon existence time, distance and platoon delay for passenger cars with FFS = 75 mph

Variable	**Platoon Type**	**Leader Speed Difference (mph)**			
		1	2	3	4
Platoon Existence Time (s)	Type I	458	228.6	152.4	114.5
	Type IV	495	247.5	165	123.8
Platoon Existence Distance (mile)	Type I	9.03	4.57	3.09	2.35
	Type IV	9.35	4.74	3.2	2.4
Platoon delay for passenger cars with 75mph free-flow-speed(s)	Type I	24.1	9.14	6.18	1.52
	Type IV	46.2	19.78	10.97	6.49

Table 6.7 Empirical analysis for average platoon existence time, distance and platoon delay for passenger cars with FFS = 75 mph

Platoon Type	**Type I**	**Type II**	**Type III**	**Type IV**
Platoon Existence Time (s)	367	530	777	1104
Platoon Existence Distance (mile)	7.56	10.01	13.46	16.93
Platoon delay for passenger cars with 75mph free-flow-speed(s/platoon)	38	59	90	140

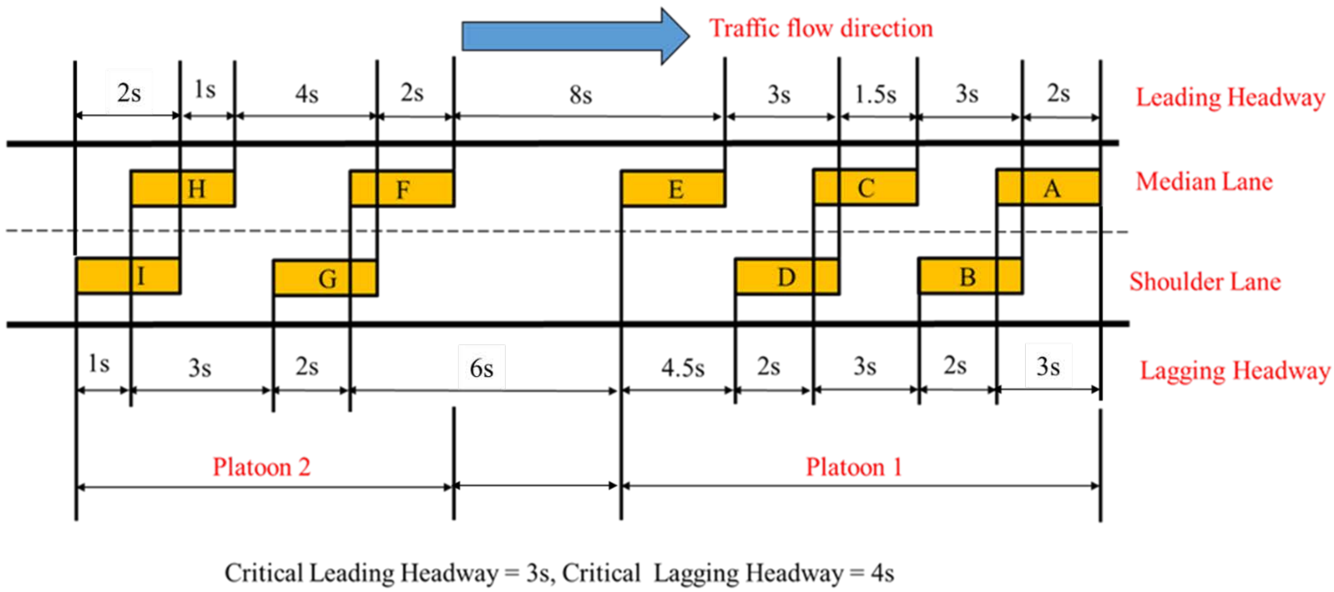

Figure 6.1 Platoon definition

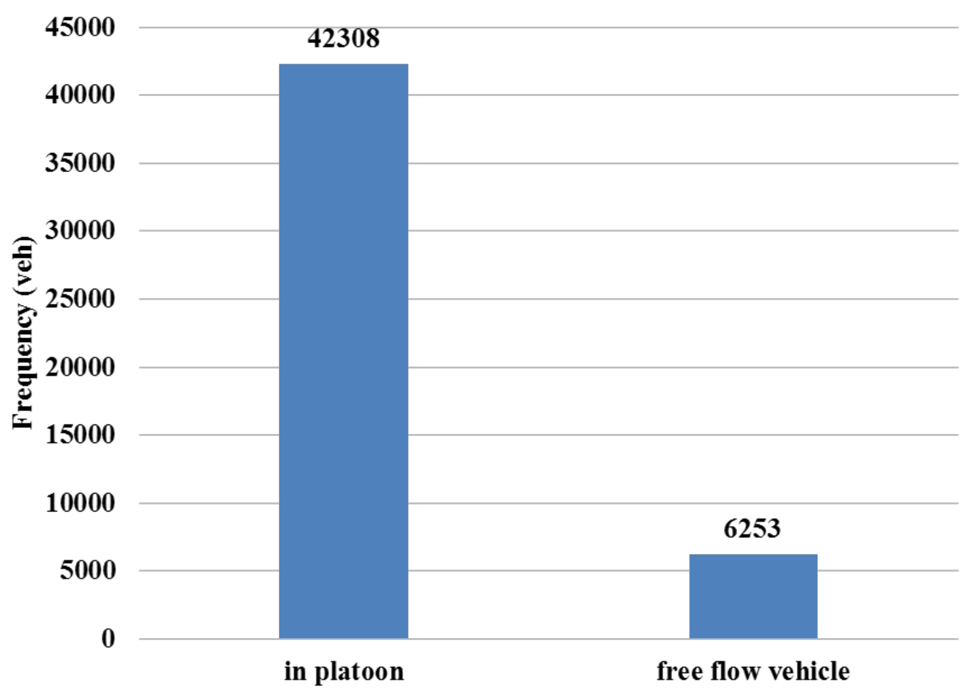

Figure 6.2 Frequency of vehicles in platoon

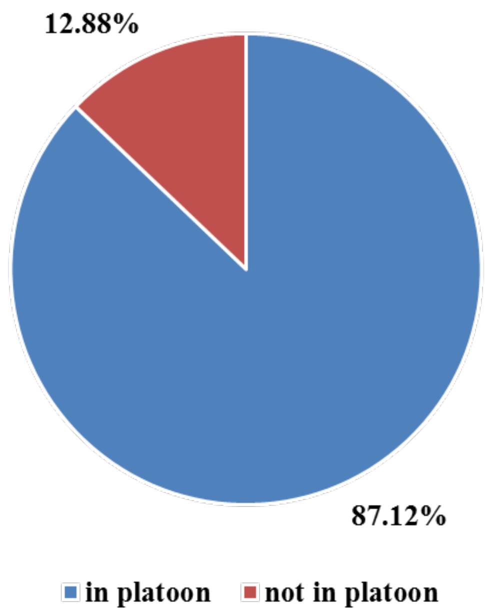

Figure 6.3 Frequency of vehicles in platoon

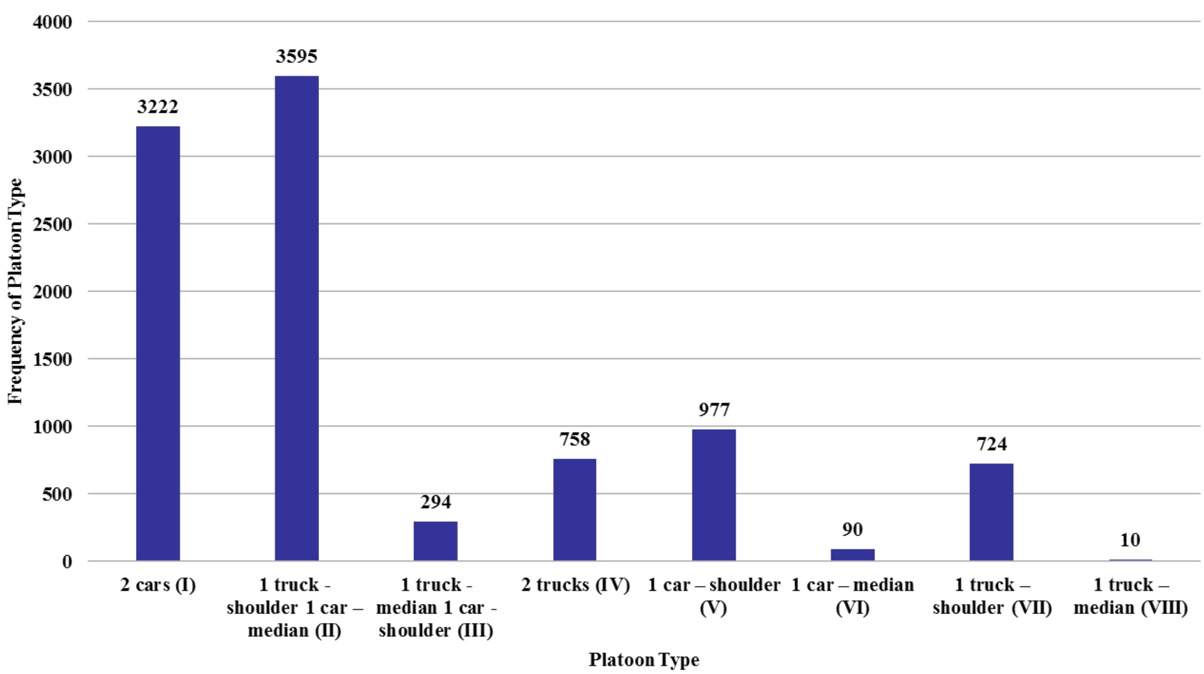

Figure 6.4 Frequency of platoon types

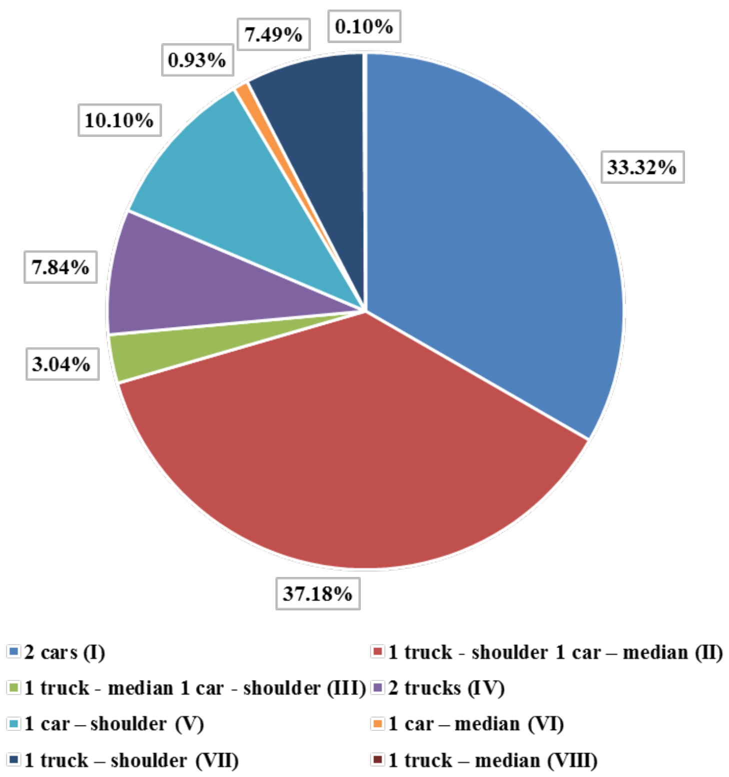

Figure 6.5 Percentage of platoon types

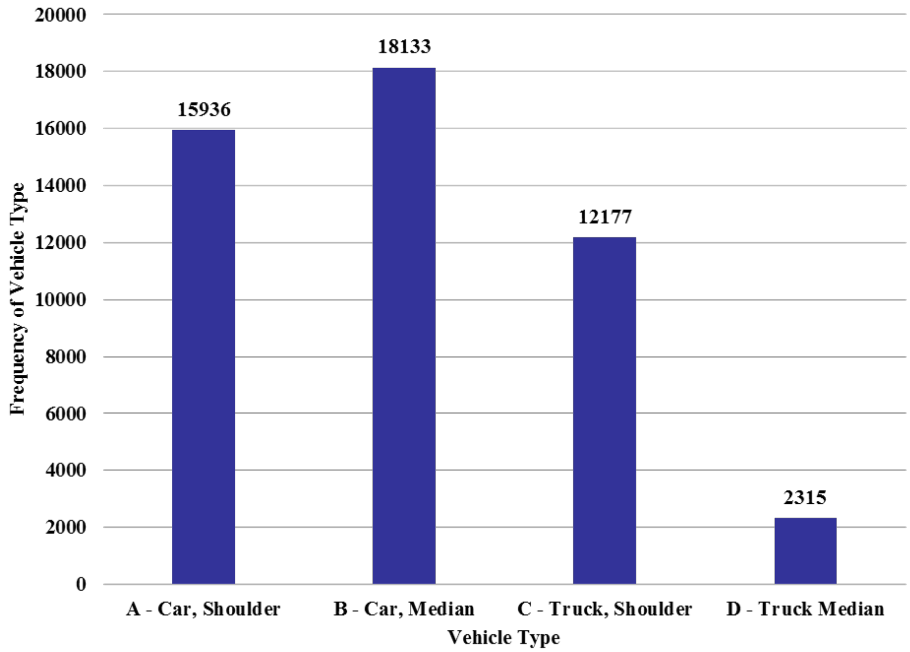

Figure 6.6 Frequency of vehicle type

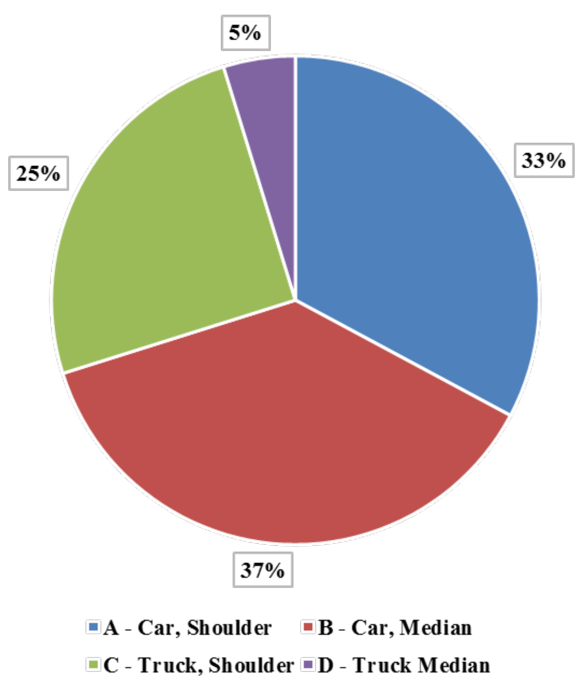

Figure 6.7 Percentage of vehicle type

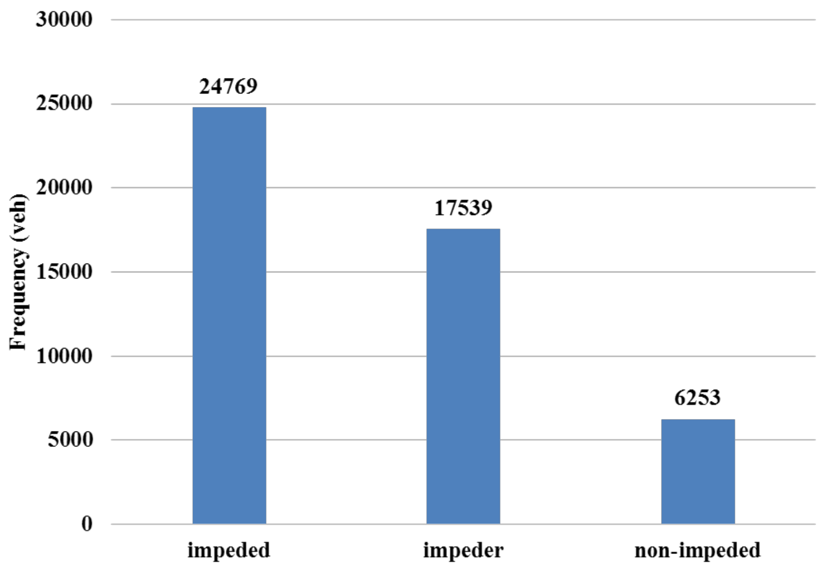

Figure 6.8 Frequency of Impeder, Impeded and Non-impeded Vehicles

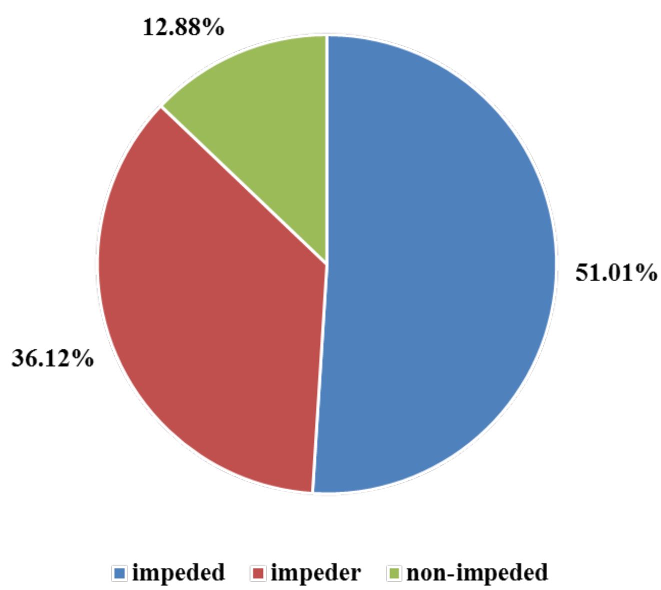

Figure 6.9 Percentage of Impeder, Impeded and Non-impeded Vehicles

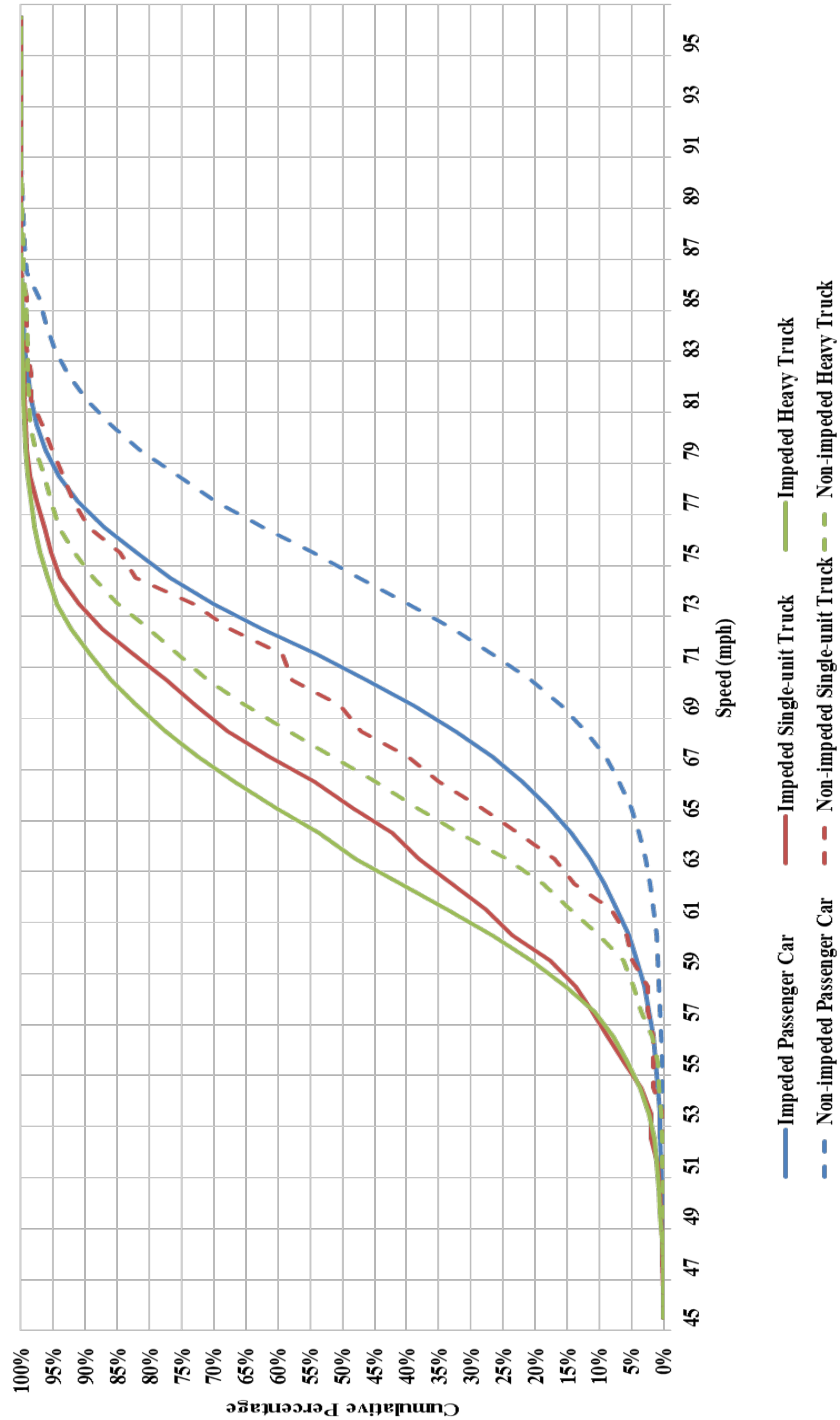

Figure 6.10 Speed distribution for impeded and non-impeded vehicles

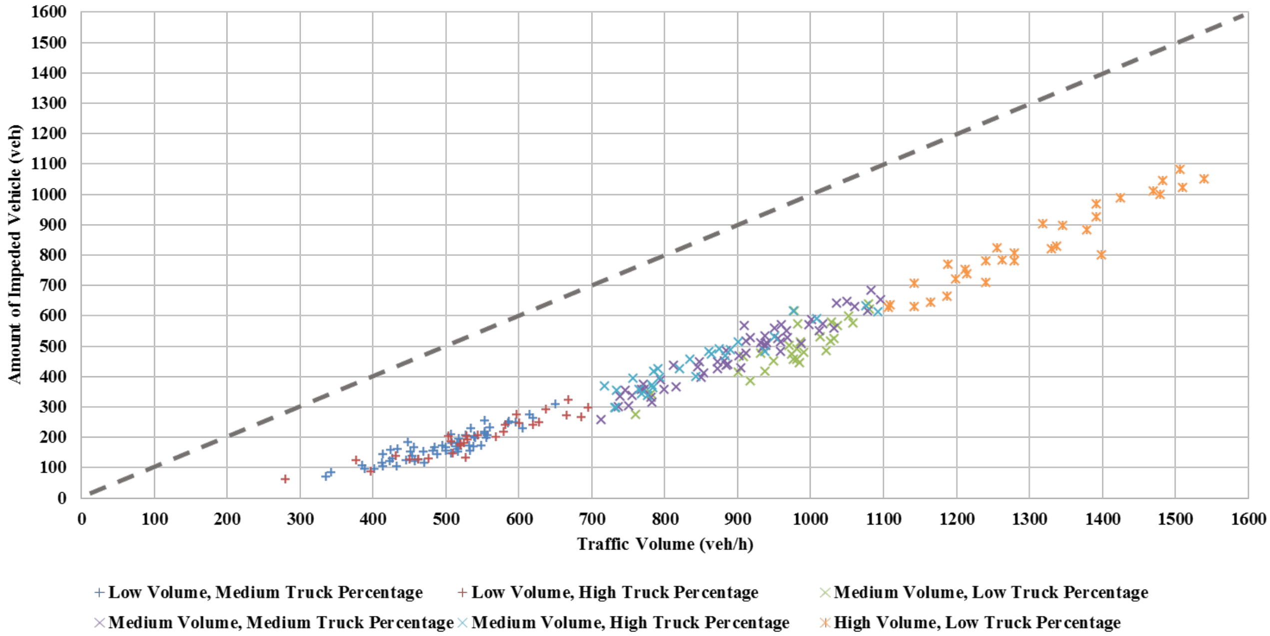

Figure 6.11 Relationship between traffic volume and amount of impeded vehicle

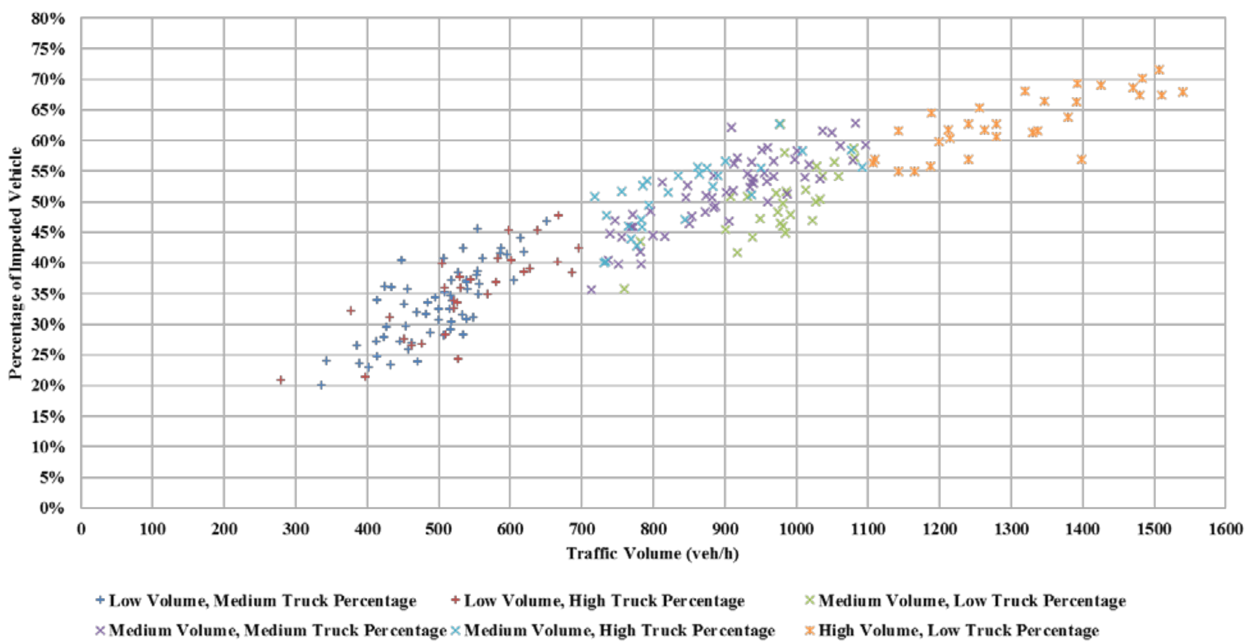

Figure 6.12 Relationship between traffic volume and percentage of impeded vehicle

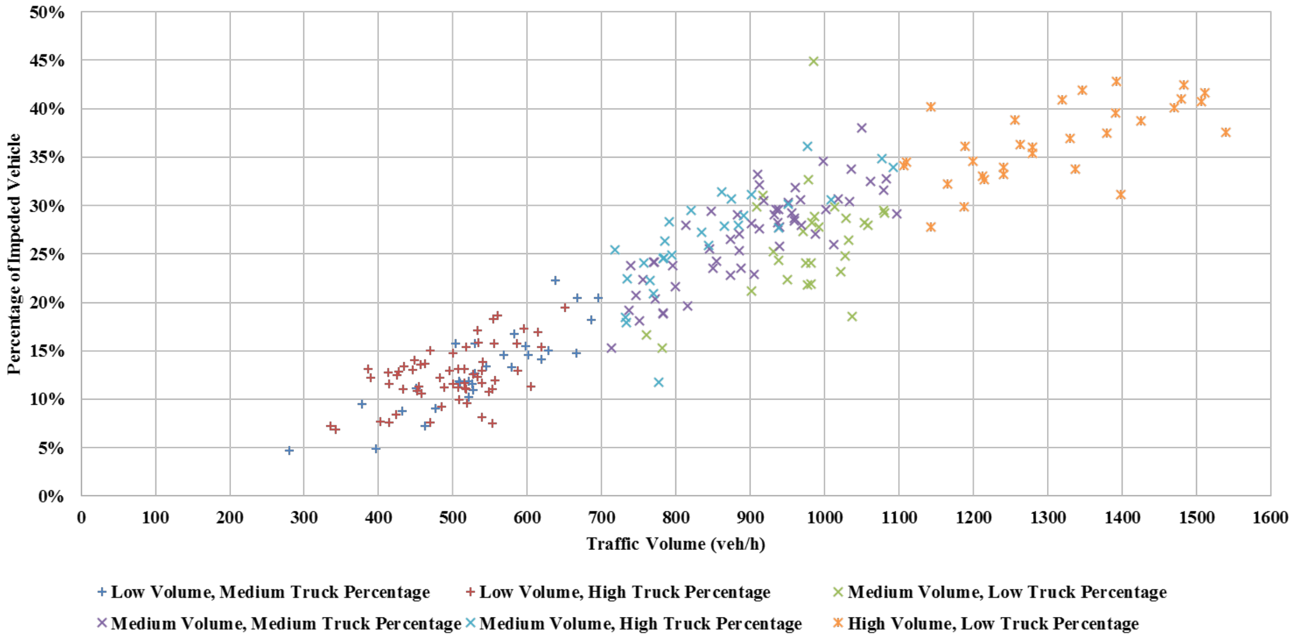

Figure 6.13 Relationship between traffic volume and percentage of time impeding

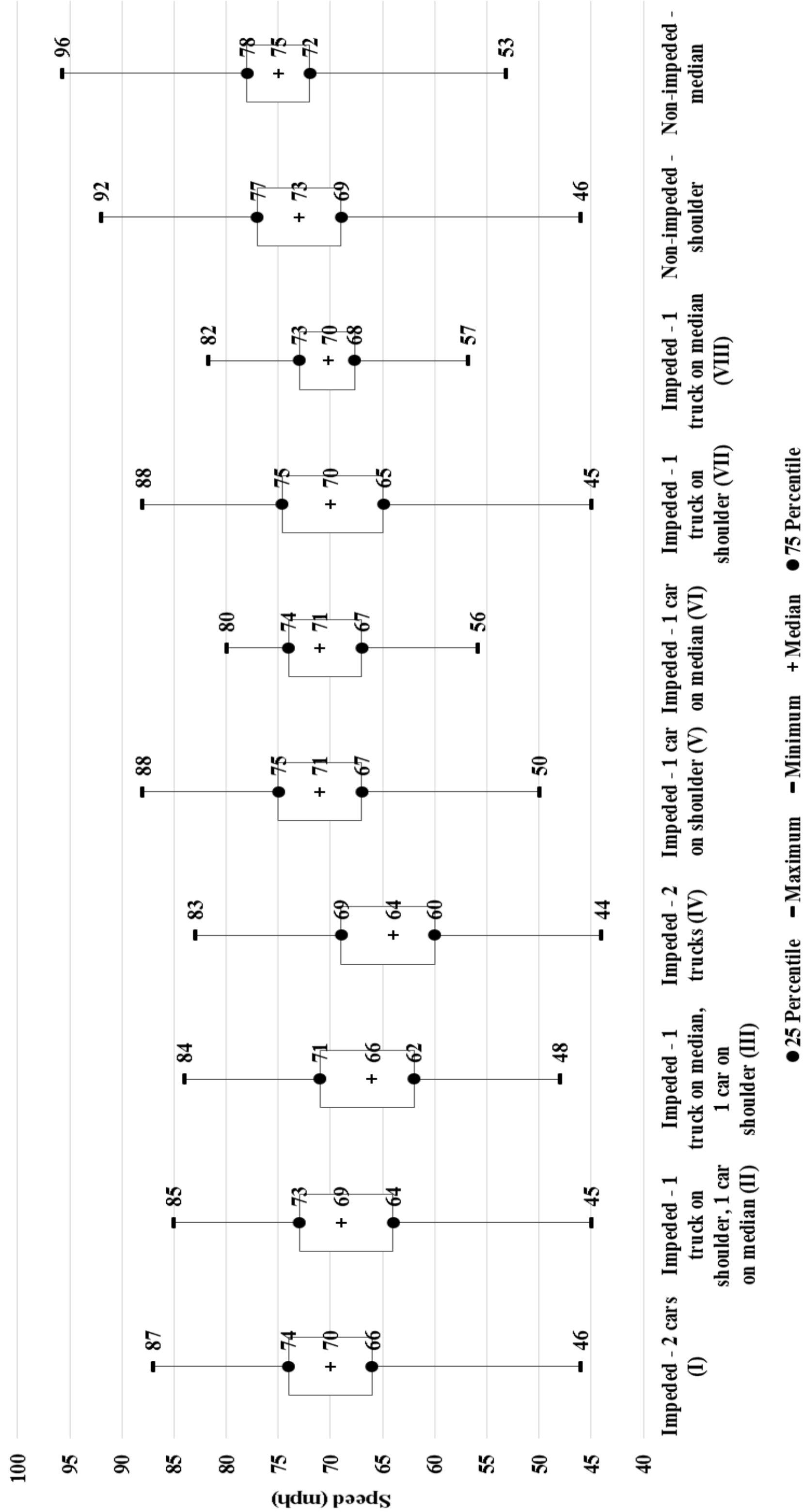

Figure 6.14 Impeded vehicle speed vs non-impeded vehicle speed (for all vehicles)

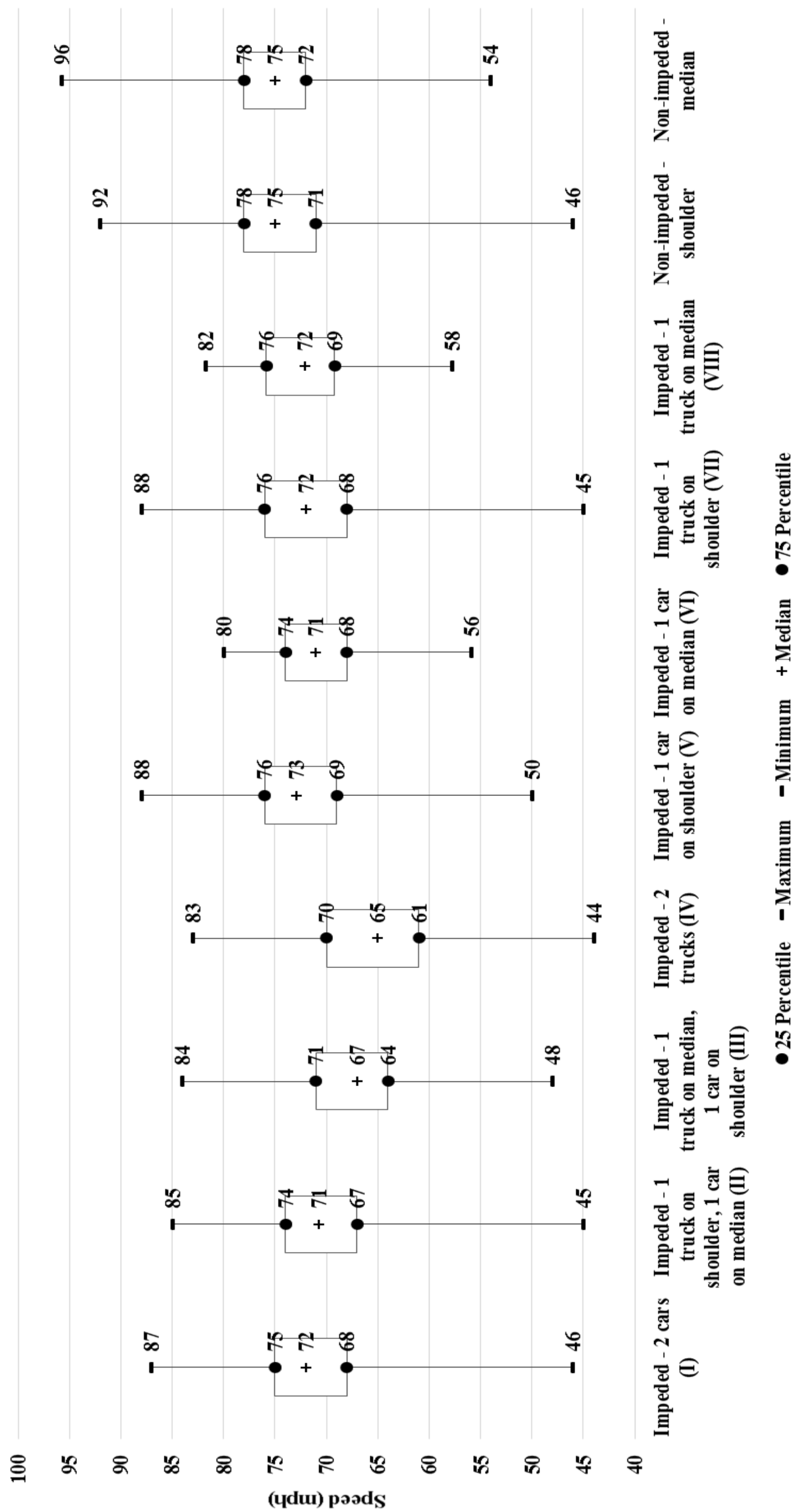

Figure 6.15 Impeded vehicle speed vs non-impeded vehicle speed (for passenger cars)

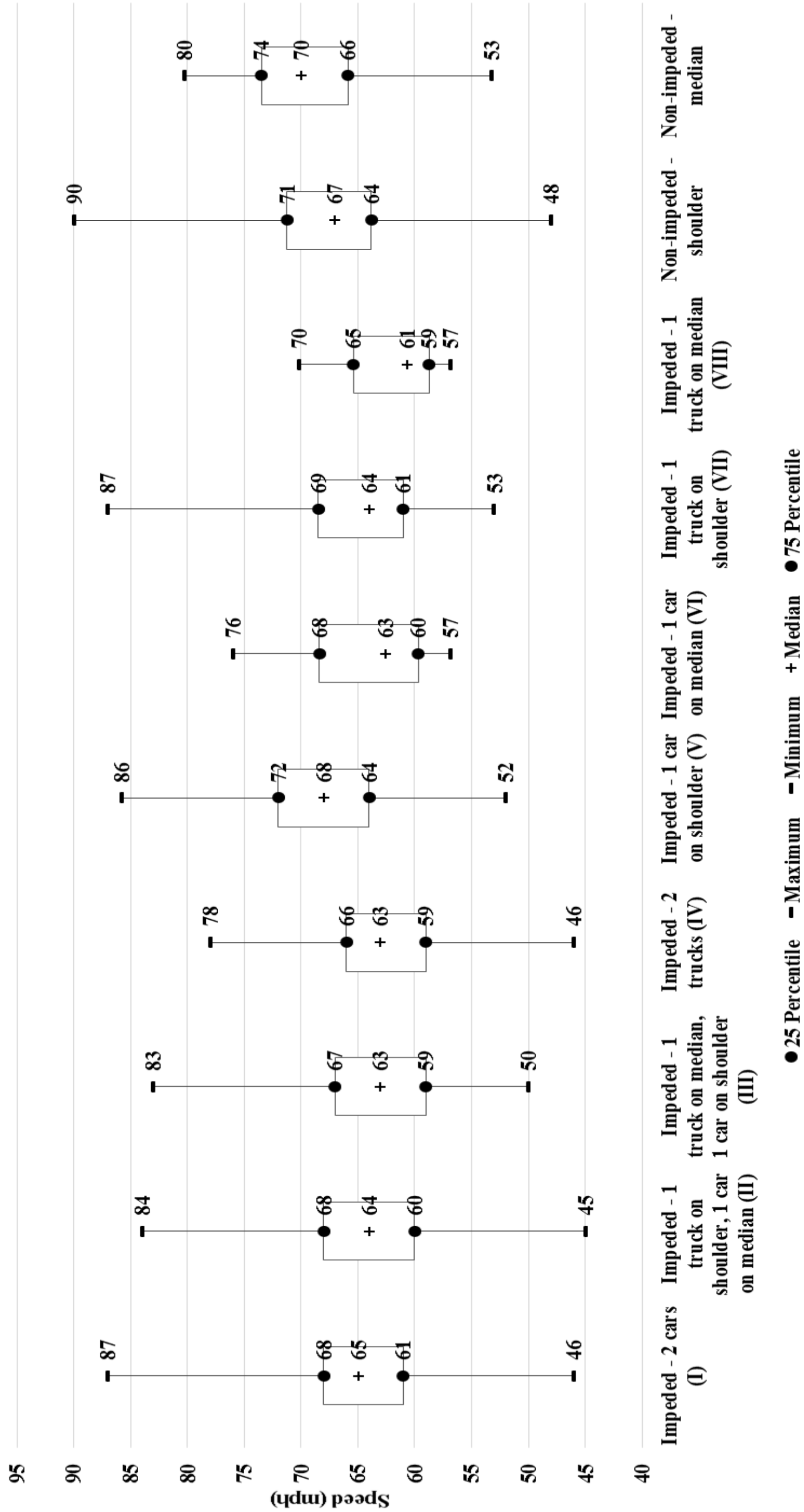

Figure 6.16 Impeded vehicle speed vs non-impeded vehicle speed (for trucks)

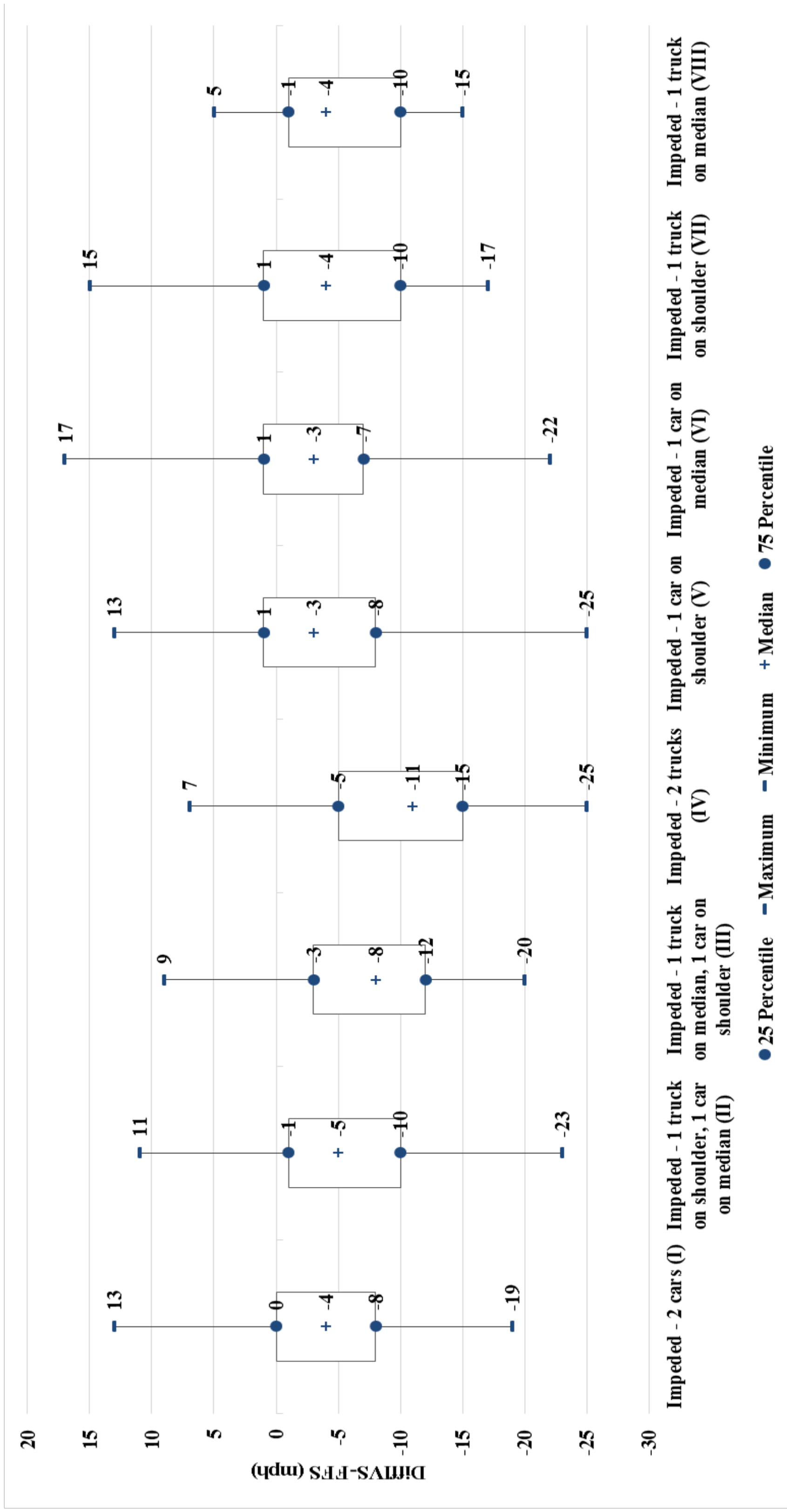

Figure 6.17 Distribution of DiffIVS-FFS for each platoon type

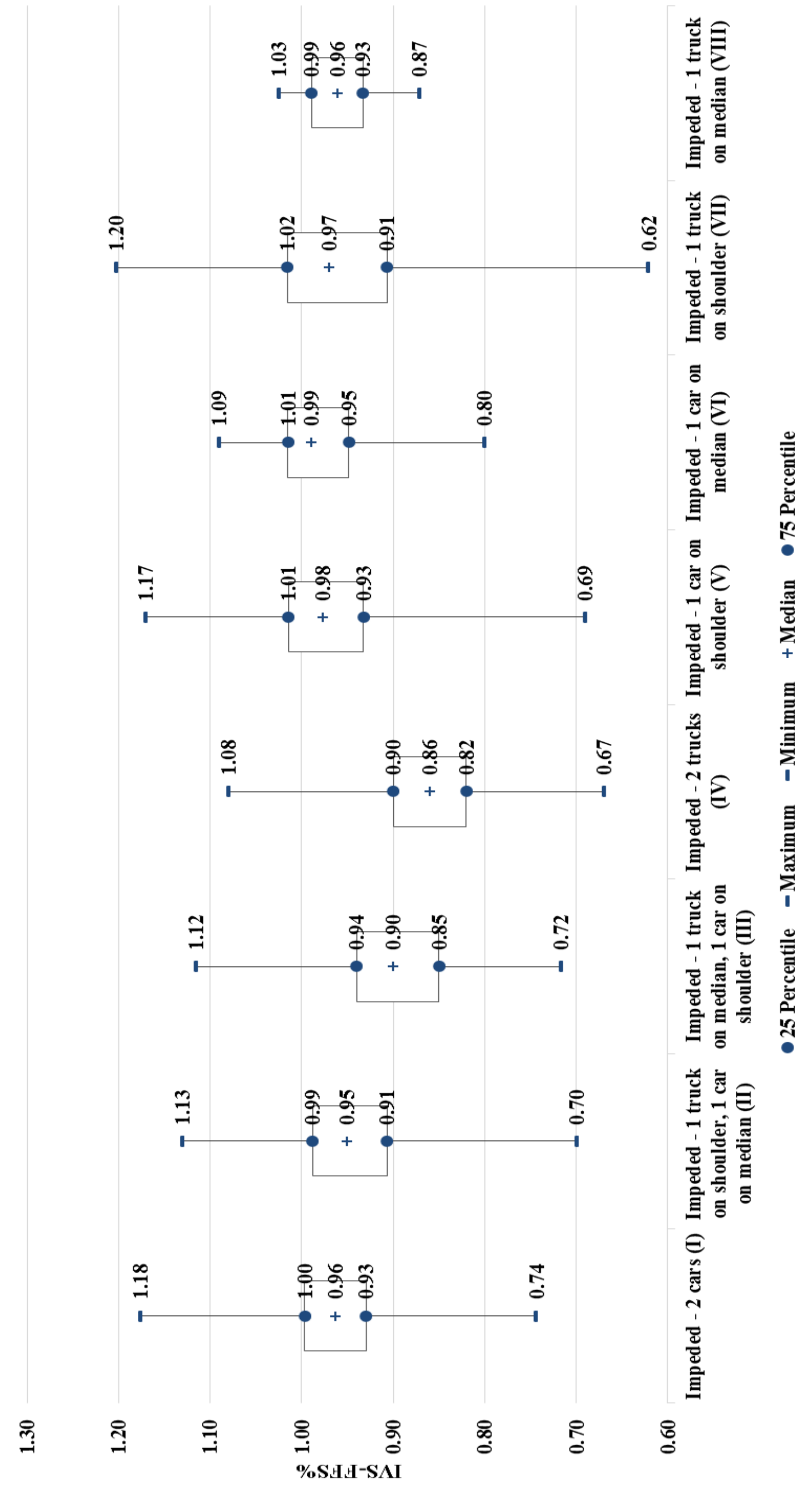

Figure 6.18 Distribution of IVS-FFS% for each platoon type

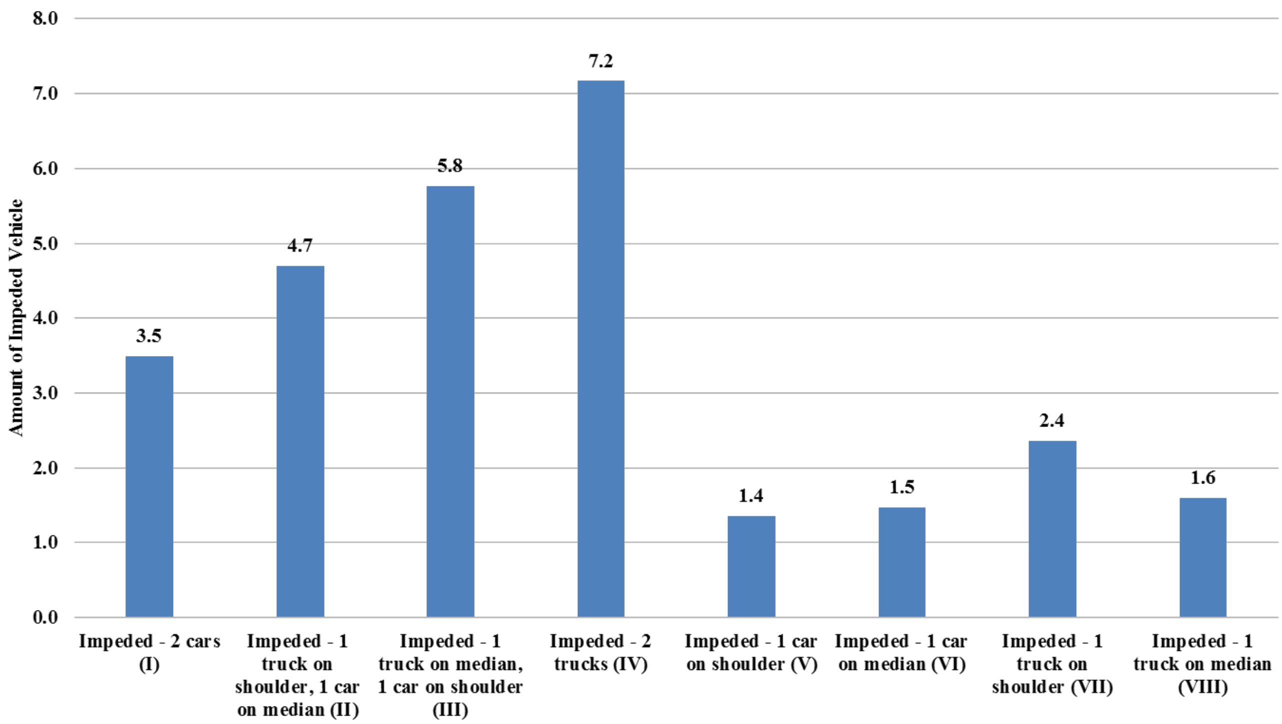

Figure 6.19 Average number of impeded vehicles for different platoon types

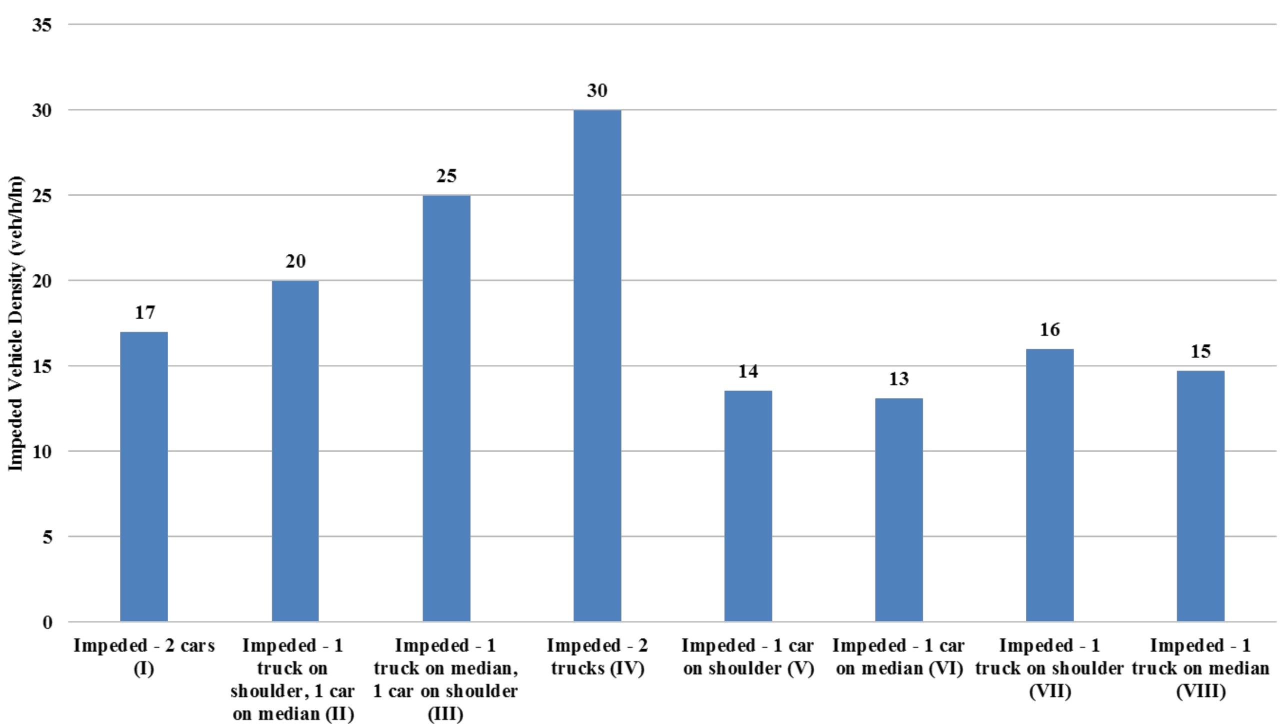

Figure 6.20 Average density of impeded vehicles for different platoon types

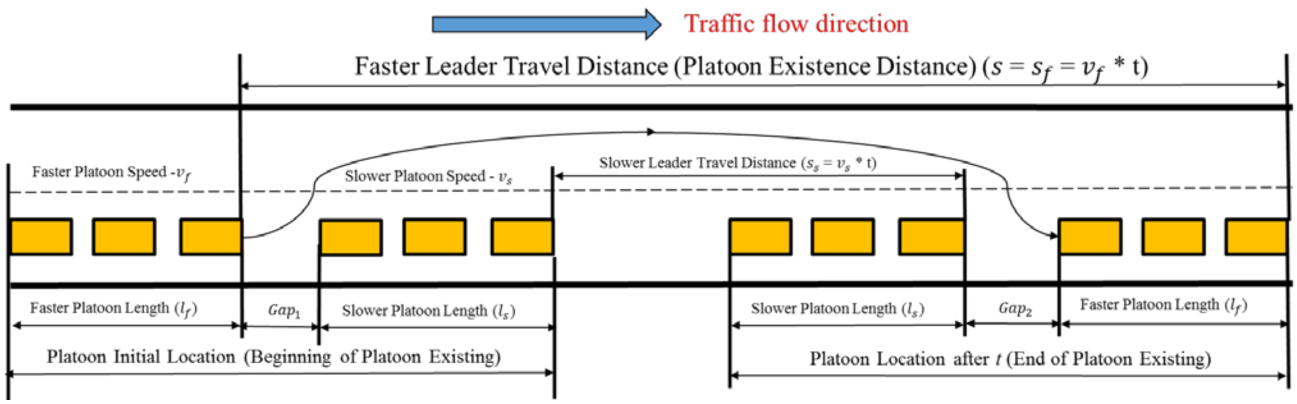

Figure 6.21 Definition of platoon existence distance and platoon existence time

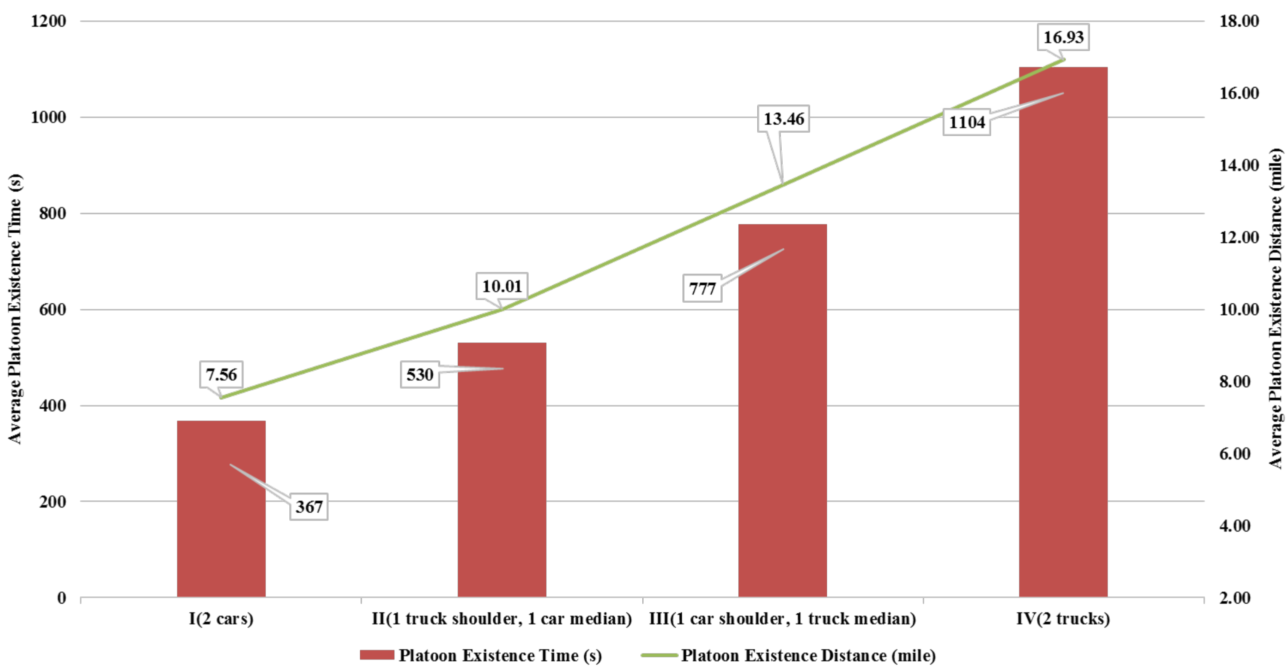

Figure 6.22 Platoon existence distance and time for different platoon types based on empirical data

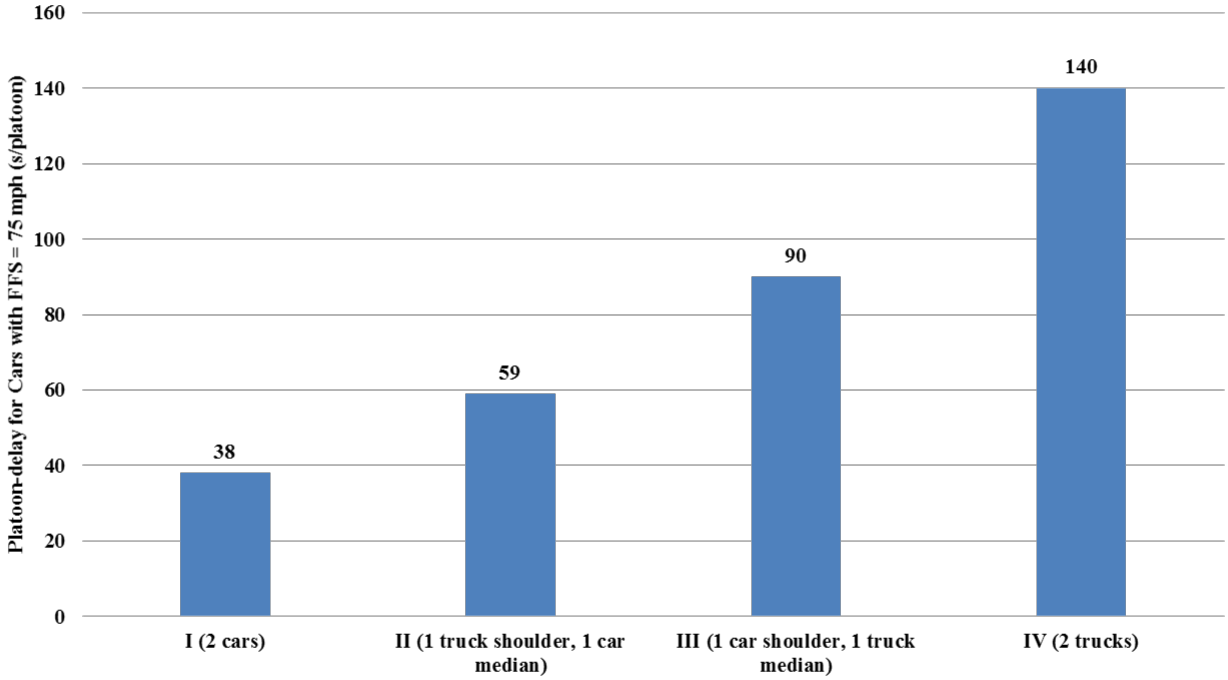

Figure 6.23 Platoon delay for passenger cars with FFS = 75 mph based on empirical data

Chapter 7 PCE Analysis with Empirical Data

In the following chapters, PCE values are estimated using three methods discussed in Chapter 2: equal-density-based method, delay-based method, and headway-based method. Because the equal-density-based method and delay-based method need to be implemented with simulation data, these are discussed in Chapter 8.

7.1 Headway-based PCE

7.1.1 Headway-based Method

The headway-based PCE (H-PCE) determination method was introduced in Chapter 2.2 using Equation 2-3, and is repeated as Equation 7-1 for convenience:

$$PCE = \frac{(1-p)(h_{pt} + h_{tp} - h_{pp}) + p * h_{tt}}{h_{pp}} \qquad (7\text{-}1)$$

$H - PCE$	- headway-based passenger car equivalents for trucks
p	- percentage of trucks at a mixed traffic stream
h_{pp}	- mean headway for passenger cars following passenger cars
h_{pt}	- mean headway for passenger cars following trucks
h_{tp}	- mean headway for trucks following passenger cars
h_{tt}	- mean headway in seconds for trucks following trucks

The headway-based method was initially proposed for PCE determination for one lane, not for two lanes. Therefore, the H-PCEs were estimated for the shoulder lane and median lane separately. The lagging headways are used for H-PCE determination. Here the modification for the headway-based method is that the critical headway determination is different from that in the original method (Krammes and Crowley, 1986). In the original method, the critical headway is determined based on the assumption that: 1) passenger car drivers in a mixed stream are affected only by trucks that are immediately preceding them; and 2) drivers of a vehicle of interest were assumed to be exhibiting steady-state, in-lane behavior if they maintained the same lane placement and same position with respect to the leading and following vehicles for 300 ft before and after the point of measurement (Krammes, 1986). The critical headway is determined based on values in Table 6.1, which means that only observations where the headways was less than the critical headways were used to estimate the H-PCE values.

For both shoulder and median lane, the 60 hours data were divided into 240 15-minute intervals. The H-PCE was first determined using all 60 hours of data. Based on Krammes' research, the H-PCEs were affected by traffic volume on all lanes and truck percentage. In order to explore the effects of traffic volume and truck percentage, the data were divided into 9 groups based on traffic volume (low, medium, and high) and truck percentage (low, medium, and high). The thresholds were listed in section 6.2.4, and H-PCEs were estimated for each group.

7.1.2 Results of Headway-based PCE

The estimated H-PCEs using all 60 hours of data are shown in Table 7.1. Table 7.1 shows that the headway value is a function of the headways for passenger car following passenger car, passenger car following truck, truck following passenger car, and truck following truck. The H-PCE was 2.3 for the shoulder lane and 2.4 for the median lane. The H-PCEs estimated for each group are shown in Table 7.2. The H-PCEs are disaggregated by lane, volume, and truck percentage. Results show that H-PCEs for median lane are higher than that for shoulder lane, increasing with traffic volume (which is similar to Krammes' conclusion), but decreasing with an increase in truck percentage. Also, the H-PCE values based on empirical data (from 2.1 to 2.5) are higher than recommended values in HCM 2010 (1.5), which means the range of the value is reasonable as expected. Note that only headways and truck percentage are used for estimating PCE values, and the effects of platoon type are not considered. The decrease in PCE with an increase in truck percentage appears to be counteractive to the hypothesis that vehicles are affected more seriously when in a platoon led by a truck at a high truck percentage condition. Thus, effects of trucks on passenger cars cannot be appropriately reflected by an H-PCE only.

7.2 Concluding Remarks

In this chapter, the PCEs are determined with empirical data using the modified headway-based method. The empirical-data-based H-PCE ranges from 2.1 to 2.5, which increases with traffic volume but decreases with an increase in truck percentage, and the value for the shoulder lane is higher than that for the median lane. Comprehensively, considering the range of values and the effects of factors (e.g. traffic volume, truck percentage and lane type) on PCEs, the H-PCEs might be appropriate for reflecting the effects of trucks on passenger cars.

Table 7.1 Results of H-PCE based on all 60 hours data

Variable	Shoulder Lane	Median Lane
cc lagging headway	1.88s	1.46s
ct lagging headway	3.70s	2.05s
tc lagging headway	3.82s	3.04s
tt lagging headway	2.68s	2.18s
Truck percentage	44%	13%
H-PCE (Equation 7-1)	2.3	2.4

*Note: cc = car following car; ct = car following truck; tc = truck following car; tt = truck following truck.

Table 7.2 Results of H-PCE for each group

Lane	Volume (veh/h)	Truck Percentage (%)		
		Low (<=25%)	Medium (>25%, <=35%)	High (>35%)
Shoulder Lane	Low (<=700)	--	--	2.1
	Medium (>700, <=1100)	--	2.2	2.2
	High (>1100)	--	2.4	2.4
Median Lane	Low (<=700)	2.4	2.2	--
	Medium (>700, <=1100)	2.4	--	--
	High (>1100)	2.5	--	--

*Note: Volume are for two lanes, -- represents lacking adequate observations for this group.

Chapter 8 PCE Analysis with Simulation Data under Nebraska Traffic Conditions

In the previous chapter, PCEs were using empirical data with the headway-based method. In this chapter, simulation data for Nebraska conditions are used. First, PCEs are estimated using the equal-density method and delay-based method. Subsequently, the simulation data are used to estimate PCEs using the headway-based method, and a comparison between the PCEs estimated by empirical and simulated data is then carried out.

8.1 Introduction to Simulation Model

In this research, the simulation data is generated by VISSIM 5.4. Because one of the most critical traffic characteristics on I-80 in Nebraska is that large numbers of platoons are observed under high truck percentage conditions, it was necessary to validate and calibrate the model for these conditions.

The simulated network was designed as a 4-link grid network, as shown in Figure 8.1. Two of the links were 3.28 miles in length, and two of the links were 2.63 miles in length. Each link is one way and has two 12 foot lanes and zero gradient. The calibrated freeway behavior parameters in VISSIM include lane change parameters (e.g., lane change distance and maximum deceleration) and parameters in Wiedemann 99 car following model (e.g., stand still distance – CC0, headway time – CC1, following variation – CC2, threshold for entering following mode – CC3, negative/positive following threshold – CC4 and CC5, and speed dependency of oscillation – CC6) (Appiah et al 2011). The geometric and behavior parameters are the same on all four road links. Vehicles enter and leave at the bottom left corner of the model. Thus, the road network is a ring where vehicles travel in a clockwise direction. This set-up was chosen for display purposes only because the network essentially acts as a linear “pipe” where vehicles enter at one end and exit at the other. The goal is to mimic the HCM base freeway segment.

All the simulations that were run consist of three parts:

(1) one-hour network loading so that the vehicles achieve a steady-state;

(2) two-hour steady-state with constant volume; and

(3) one-hour traffic unloading.

Only the data from the 2 hour steady state conditions are analyzed. The two variables that were examined were traffic volume and truck percentage. The traffic volume ranged from 500 veh/h to 1500 veh/h at intervals of 200 veh/h resulting in six levels. The truck percentage ranged from 0% to 90% at intervals of 5%, resulting in 19 levels.

Vehicles are grouped into three classifications: passenger cars, single-unit trucks, and heavy trucks. In order to mimic Nebraska conditions, the volume of single unit trucks was set to ten percent of the heavy truck volume, and this ratio is based on empirical data. In addition, each vehicle type attempts to follow the free flow empirical speed distribution shown in Figure 8.2.

Four data collection points are chosen and set at equal distance on the network in total. At each data collection point one detector is set for each lane. Eight data detectors are used in total, where information at that point and across time can be obtained. The output data obtained at each data collection point includes detector on and off times, vehicle type, vehicle length, vehicle speed, and vehicle travel time between detectors and delay.

For each combination of variables, two scenarios were modeled. The first, known as the Nebraska scenario, allows trucks in both lanes and hence passing is allowed. The Nebraska scenario mimics actual Nebraska conditions. The second, known as the truck restriction scenario, bans trucks from the median lane. In other words trucks are not allowed to pass. This scenario is used for comparison purposes, which will be discussed in Chapter 9.

8.2 PCE under Nebraska Condition

8.2.1 Equal-density-based PCE

The equal-density-based PCE (ED-PCE) determination method was introduced in section 5.1.2. Following HCM practice, the proportion of subject vehicles added to the mixed traffic and subtracted from the base flow is set to five percent. As discussed previously, the HCM 2010 assumes that all vehicles have the same desired (e.g., free flow) speed distribution. However, the empirical data from Nebraska indicated that different vehicles have different desired speeds. PCEs were calculated under both assumptions (e.g., same and different) and compared.

There are five steps for calculating the HCM PCE values based on the equal density method, known as ED-PCE, as shown below.

Step 1 Develop the volume-density curve for the base flow (e.g., only passenger cars) using simulated data. The hourly volume rate is estimated based on a 15-min interval traffic volume, and the density is estimated by dividing the 15-min based hourly volume rate by the average speed in a 15-min interval.

Step 2 Develop volume-density curve for mixed flow using simulated data. Hourly volume rate and density are estimated similar to Step 1. The truck percentage ranges from 5% to 85% at intervals of 10%.

Step 3 Develop volume-density curve for the subjected flow condition. Hourly volume rate and density are estimated similar to step 1. The change in truck percentage is five percent. This corresponds to a new truck percentage (e.g., compared to Step 2) that ranges from 10% to 90% at intervals of 10%.

Step 4 The subjected volume is modeled for volumes from 500 veh/h to 1500 veh/h at intervals of 200 veh/h. For each subjected flow volume, the density is obtained from the volume-density curve for the subjected flow condition. Then, the volume for mixed flow and based flow at the same density are obtained from the volume-density curves for the mixed flow and base flow conditions.

Step 5 The ED-PCE is estimated using equation 5-1 for each combination of parameters.

Note that the above steps were first used for the three vehicle speed distributions. Then they were subsequently run assuming the one speed distribution. The volume-density curves at different truck percentage for Nebraska scenario conditions are shown in appendix.

The ED-PCE results for the Nebraska scenario assuming three speed distributions are shown in Table 8.1 and Figure 8.3. It may be seen that the ED-PCE value ranges from 2.6 to 3.4 with an average value of approximately 3.0 for the Nebraska scenario using vehicle-specific empirical speed distribution conditions. Note that this scenario is representative of Nebraska conditions.

The ED-PCE results for the Nebraska scenario assuming a one speed distribution are shown in Table 8.2 and Figure 8.4. It may be seen that the ED-PCE value ranges from 1.5 to 2.1 with average value of approximately 1.8 for the Nebraska scenario using one empirical speed distribution. These results indicate that using a one speed distribution for all vehicles, as was done in the HCM, leads to a lower PCE value, which would be expected. It should be noted that the average value of 1.7, for truck percentages of less than 25%, is relatively close to the HCM value of 1.5. The average ED-PCEs as a function of traffic volume assuming three speed distributions are shown in Table 8.3 and Figure 8.5. The average ED-PCEs as a function of truck percentage assuming two speed distribution conditions are shown in Table 8.4 and Figure 8.6.

Also, AVONA analyses are implemented to explore the effects of traffic volume and truck percentage on ED-PCEs for different and same speed distribution conditions. Results of ANOVA analyses show that, for the Nebraska condition, no matter three or one speed distributions, are used. The ED-PCE is not significantly affected by truck percentage, but significantly increases with traffic volume; and the ED-PCE under three speed distributions is significantly higher than that for a one speed distribution. The ED-PCE values based on empirical speed distribution for all combinations of traffic volume and truck percentage are higher than 1.5, as reasonably expected.

8.2.2 Delay-based PCE

The delay-based PCE (D-PCE) determination method was introduced in Chapter 2.2, and it is based on the following equation:

$$PCE = 1 + \frac{\Delta d_t}{d_0} \tag{8-1}$$

PCE	- passenger car equivalents for trucks
Δd_t	- additional delay caused by per truck
d_0	- average delay per vehicle of passenger car when truck percentage is 0% (base delay)

The D-PCE was initially proposed for PCE determination at signalized interactions, but the concept has been extended for determining PCEs on roadways where there is considerable vehicle speed reduction and congestion. It is hypothesized that because of the large amount of platooning on I-80 in Nebraska, and the associated reduction in speed, that this approach might be appropriate for Nebraska.

Zhao (1996) found that D-PCEs are effected by traffic volume and truck percentage. Therefore, in this report D-PCE are estimated for various combinations of traffic volume and truck percentage. The traffic volume is divided into six levels, ranging from 500 veh/h to 1500 veh/h at inverals of 200 veh/h, and the truck percentage is divided into 18 levels, ranging from 5% to 90% at intervals of 5%. The D-PCEs are estimated based on the assumption that different vehicle classes have three speed distributions. The average delay per passenger car when the truck percentage is 0% and the average additional delay caused per truck in 15-minute intervals are used to estimate the D-PCE.

The estimated D-PCEs for the Nebraska scenario are shown in Table 8.5 and Figure 8.7. It may be seen that the D-PCE value ranges from 1.8 to 4.9 with an average of 2.8. In addition, it may be seen that the estimated D-PCE value increases with truck percentage, and this relationship is approximately linear. For all combinations of traffic volume and truck percentage, the D-PCEs are higher than 1.5, as reasonably expected. The average D-PCEs at different traffic volume and truck percentages are as shown in Table 8.6 and Table 8.7.

Also, AVONA analyses are implemented to explore the effects of traffic volume and truck percentage on D-PCEs. The results of ANOVA analyses show that, for the Nebraska condition, the D-PCE significantly increases with traffic volume and truck percentage.

8.2.3 Headway-based PCE

The method for H-PCE determination based on simulation data is exactly the same as that used on the empirical data described in chapter 7.1.1. The H-PCE are estimated for the shoulder and median lane separately. In addition, they are estimated for different combinations of traffic volume and truck percentage. The levels of traffic volume and truck percentage are described in section 8.2.2. Similar to section 8.2.2 it is assumed that the vehicle types all follow three empirical speed distributions.

The estimated H-PCEs for the Nebraska scenario are shown in Table 8.8. The H-PCEs for the shoulder and median lanes are shown in Figure 8.8 and Figure 8.9, respectively. It may be seen that the H-PCEs based on simulation data range from 1.7 to 3.1. In contrast, the H-PCEs based on empirical data range from 2.1 to 2.5. However, there is more range in the simulated conditions than in the empirical conditions. When similar volumes and truck percentage are compared, the simulated H-PCEs are, on average, 5% higher than the empirical values. The H-PCEs based on simulation data for shoulder and median lanes, which are 2.4 and 2.5 respectively, are a little higher but close to H-PCEs based on empirical data.

AVONA analyses are implemented to explore the effects of traffic volume, truck percentage, and lanes on H-PCEs. The average H-PCEs at different traffic volumes, truck percentages, and lanes are as shown in Table 8.9 to Table 8.11.

Results show that based on simulation data, the H-PCE significantly increases with traffic volume and decreases with an increase in truck percentage. Also, the H-PCE for a median lane is significantly higher than for shoulder lanes.

8.3 Concluding Remarks

In this chapter, a VISSIM-based simulation model is established and used for generating simulation data, and PCEs based on equal-density, delay, and headway methods under the Nebraska condition are calculated respectively using these simulation data. The road network in the simulation model is set as a ring with vehicles circling in it clockwise for 8 hours for one simulation process, and the input desired speed distribution is set as the empirical speed distributions for free flow vehicles. The traffic volume and truck percentage are considered as two affecting factors and set from 500 veh/h to 1500 veh/h and 0% to 90%, respectively. Under the Nebraska scenario, the ED-PCEs significantly increase with traffic volume, with an average of 3.0 for three speed distributions, and 1.8 for one speed distribution, indicating that the same speed assumptions made in the HCM 2010 are not suitable for PCE determination in Nebraska. The D-PCEs significantly increase with traffic volume and truck percentage with an average of 2.8. The tendencies for effects of factors (e.g., traffic volume, truck percentage and lane type) on H-PCEs based on simulation data are the same as that based on empirical data, and the ranges of simulation-data-based H-PCEs cover the ranges of the empirical-data-based values with similar averages. Comprehensively, considering the range and affecting factors, the PCEs based on the equal-density method and delay method are recommended for describing effects of trucks on passenger cars in Nebraska.

Table 8.1 ED-PCEs for three speed distributions

Traffic Volume (veh/h)	**Truck Percentage (%)**								
	5	15	25	35	45	55	65	75	85
500	2.7	3.2	3.0	2.9	3.0	2.8	2.7	2.9	2.9
700	2.7	3.0	3.1	2.8	2.9	2.7	2.6	3.0	2.8
900	2.8	2.8	2.9	3.0	3.0	2.8	2.8	3.1	2.9
1100	3.0	2.9	3.1	3.1	3.1	3.0	3.2	2.9	3.0
1300	3.1	3.0	3.0	3.1	3.2	3.2	3.4	3.2	3.3
1500	3.3	3.2	3.2	--	--	--	--	--	--

*Note: -- represents lacking adequate observations for this group.

Table 8.2 ED-PCEs for one speed distribution

Traffic Volume (veh/h)	**Truck Percentage (%)**								
	5	15	25	35	45	55	65	75	85
500	1.7	1.9	1.8	1.7	1.8	1.7	1.7	1.6	1.7
700	1.9	1.7	1.8	1.7	1.7	1.8	1.5	1.5	1.8
900	1.7	1.6	1.9	1.8	2.0	1.9	1.6	1.7	1.8
1100	1.8	1.8	1.9	1.8	1.9	2.0	1.8	1.8	1.9
1300	1.9	2.0	2.0	1.9	1.9	2.0	1.9	1.8	2.1
1500	2.0	2.1	2.1	--	--	--	--	--	--

*Note: -- represents lacking adequate observations for this group.

Table 8.3 Average ED-PCEs for different traffic volumes

Speed Distribution	**Traffic Volume (veh/h)**					
	500	700	900	1100	1300	1500
Three	2.9	2.9	2.9	3.0	3.2	3.2
One	1.7	1.7	1.8	1.9	1.9	2.1

Table 8.4 Average ED-PCEs for different truck percentages

Speed Distribution	Truck Percentage (%)								
	5	15	25	35	45	55	65	75	85
Three	2.9	3.0	3.1	3.0	3.0	2.9	2.9	3.0	3.0
One	1.8	1.9	1.9	1.8	1.9	1.9	1.7	1.7	1.9

Table 8.5 Results of D-PCEs

Truck Percentage (%)	Traffic Volume (veh/h)					
	500	700	900	1100	1300	1500
5	1.8	1.9	1.8	1.9	1.9	2.0
10	2.0	2.1	1.9	2.2	2.2	2.3
15	2.1	2.3	2.2	2.4	2.6	2.5
20	2.3	2.2	2.4	2.6	2.6	2.7
25	2.2	2.3	2.5	2.5	2.8	2.6
30	2.4	2.5	2.6	2.7	2.7	2.8
35	2.5	2.3	2.5	2.6	2.8	2.9
40	2.6	2.5	2.4	2.6	3.0	2.9
45	2.5	2.7	2.6	2.7	2.9	3.1
50	2.8	2.6	2.8	2.9	3.1	3.3
55	2.7	2.8	2.9	3.1	3.4	3.5
60	2.9	3.0	3.1	3.3	3.6	3.5
65	3.0	3.1	3.3	3.5	3.8	3.7
70	3.2	3.3	3.6	3.5	3.8	3.8
75	3.2	3.1	3.4	3.6	3.8	4.0
80	3.3	3.2	3.5	3.8	4.0	4.3
85	3.5	3.7	3.8	3.9	4.2	4.6
90	3.6	3.8	3.8	4.1	4.4	4.9

Table 8.6 Average D-PCEs for different traffic volume

Traffic volume (veh/h)	500	700	900	1100	1300	1500
D-PCE	2.7	2.7	2.8	3.0	3.2	3.3

Table 8.7 Average D-PCEs for different truck percentage

Truck Percentage (%)	5	10	15	20	25	30	35	40	45
D-PCE	1.9	2.1	2.3	2.5	2.5	2.6	2.6	2.7	2.8
Truck Percentage (%)	50	55	60	65	70	75	80	85	90
D-PCE	2.9	3.1	3.2	3.4	3.5	3.5	3.7	4.0	4.1

Table 8.8 Results of H-PCEs

Lane	**Truck Percentage (%)**	**Traffic Volume (veh/h)**					
		500	700	900	1100	1300	1500
Shoulder Lane	5	2.4	2.7	2.4	2.5	2.5	2.6
	10	2.3	2.7	2.6	2.5	2.8	2.9
	15	2.3	2.2	2.4	2.7	2.5	2.9
	20	2.2	2.4	2.3	2.4	2.9	2.8
	25	2.5	2.6	2.5	2.4	2.7	2.5
	30	2.2	2.2	2.7	2.5	2.6	2.9
	35	2.2	2.1	2.4	2.5	2.6	2.8
	40	2.4	2.1	2.6	2.5	2.8	2.5
	45	2.4	2.1	2.2	2.5	2.3	2.5
	50	2.3	2.3	2.3	2.5	2.6	2.5
	55	2.4	2.3	2.5	2.6	2.2	2.3
	60	2.2	2.2	2.1	2.4	2.6	2.3
	65	1.9	2.1	2.2	2.1	2.2	2.5
	70	2.1	2.0	2.1	2.2	2.4	2.3
	75	2.1	2.3	2.3	2.2	2.3	2.4
	80	2.2	1.9	2.0	2.3	2.2	2.2
	85	2.0	2.1	2.2	2.1	2.6	2.2
	90	1.7	2.1	2.1	2.0	2.3	2.1
Median Lane	5	2.7	2.8	2.6	2.5	2.6	2.9
	10	2.7	2.8	2.8	2.6	2.8	2.6
	15	2.6	2.6	2.8	2.4	2.7	2.7
	20	2.7	2.5	2.8	2.8	2.7	3.0
	25	2.5	2.5	2.7	2.3	2.5	3.0

	30	2.7	2.4	2.7	2.6	2.8	2.5
	35	2.6	2.3	2.4	2.5	2.4	2.9
	40	2.3	2.3	2.6	2.4	2.7	2.5
	45	2.5	2.2	2.5	2.6	2.8	2.9
	50	2.2	2.4	2.7	2.4	2.4	2.7
	55	2.3	2.1	2.4	2.3	2.7	2.5
	60	2.3	2.4	2.5	2.3	2.2	2.5
	65	2.2	2.1	2.2	2.4	2.5	2.4
	70	2.2	2.2	2.1	2.2	2.5	2.7
	75	2.1	2.1	2.1	2.5	2.1	2.4
	80	2.3	2.1	2.1	2.2	2.3	2.6
	85	1.9	2.0	2.4	2.4	2.0	2.3
	90	2.1	2.2	2.2	2.1	2.0	2.1

Table 8.9 Average H-PCEs for different traffic volume

Traffic volume (veh/h)	500	700	900	1100	1300	1500
H-PCE	2.3	2.3	2.4	2.4	2.5	2.6

Table 8.10 Average H-PCEs for different truck percentage

Truck Percentage (%)	5	10	15	20	25	30	35	40	45
H-PCE	2.6	2.7	2.6	2.6	2.6	2.6	2.5	2.5	2.5
Truck Percentage (%)	50	55	60	65	70	75	80	85	90
H-PCE	2.4	2.4	2.3	2.2	2.3	2.2	2.2	2.2	2.1

Table 8.11 Average H-PCEs for different lanes

Lane	Shoulder	Median
H-PCE	2.4	2.5

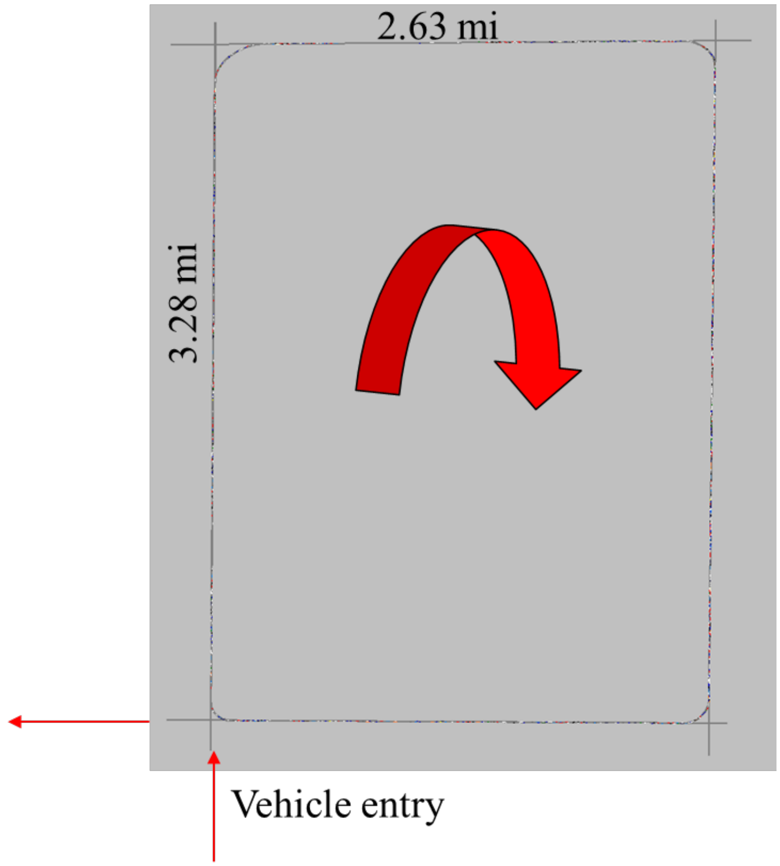

Figure 8.1 Simulation model established in VISSIM

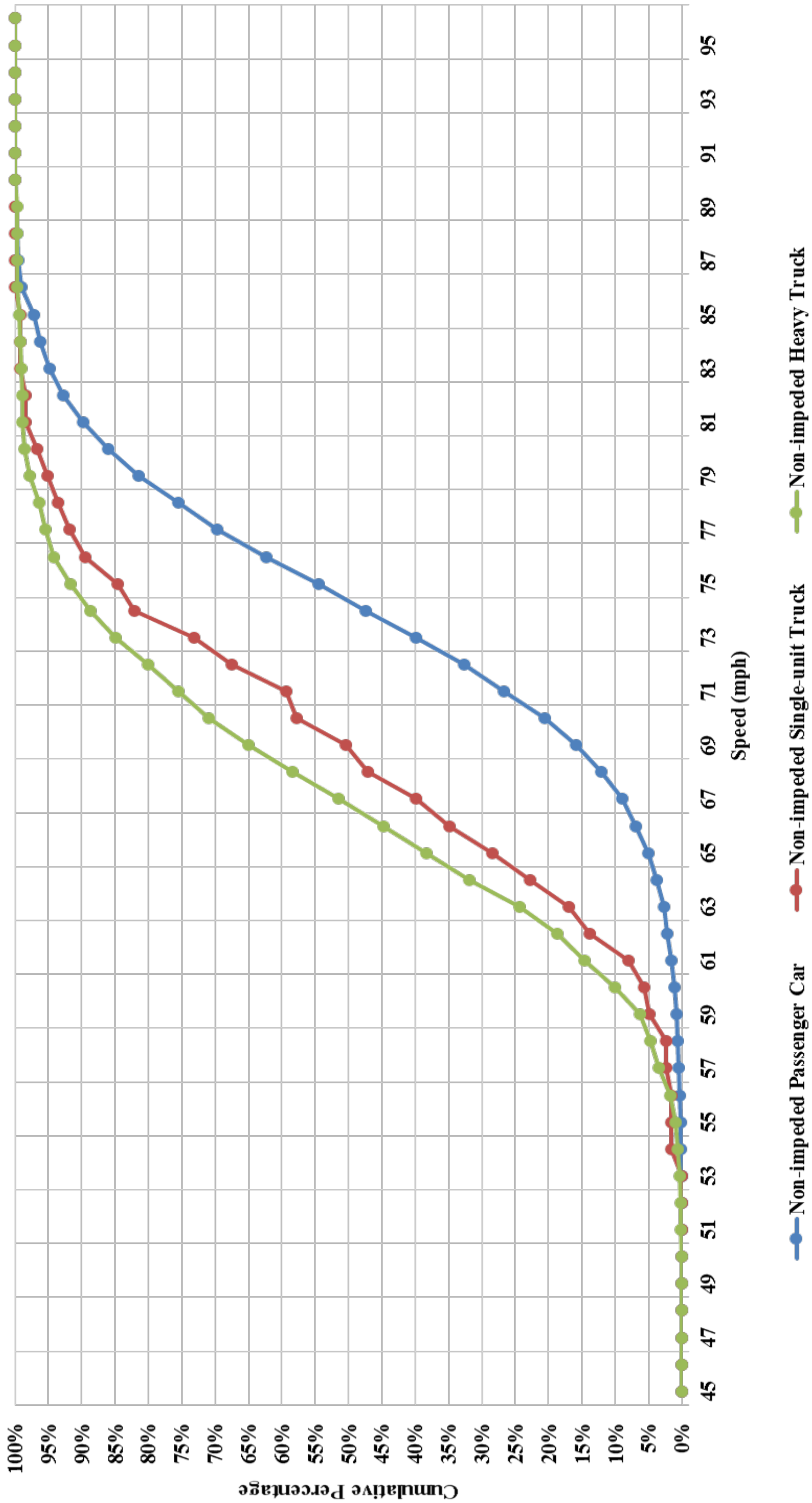

Figure 8.2 Input desired speed distribution for simulation model

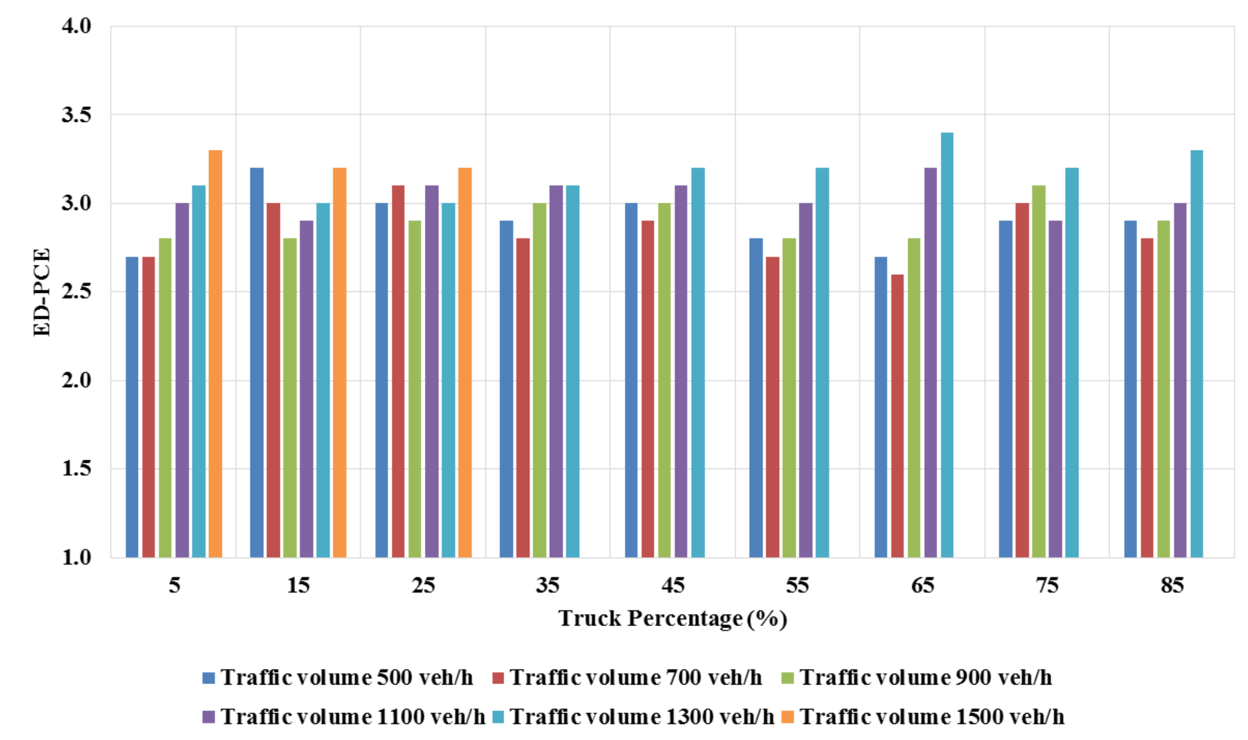

Figure 8.3 ED-PCEs for three speed distributions

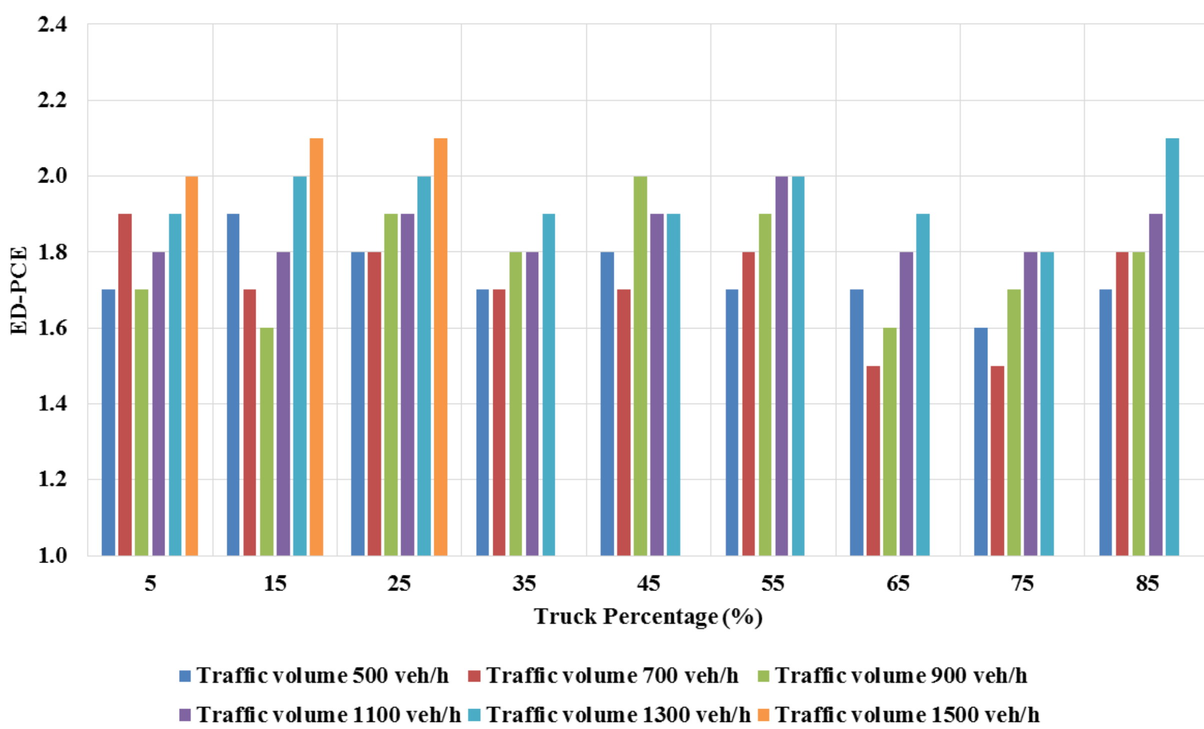

Figure 8.4 ED-PCEs for one speed distribution

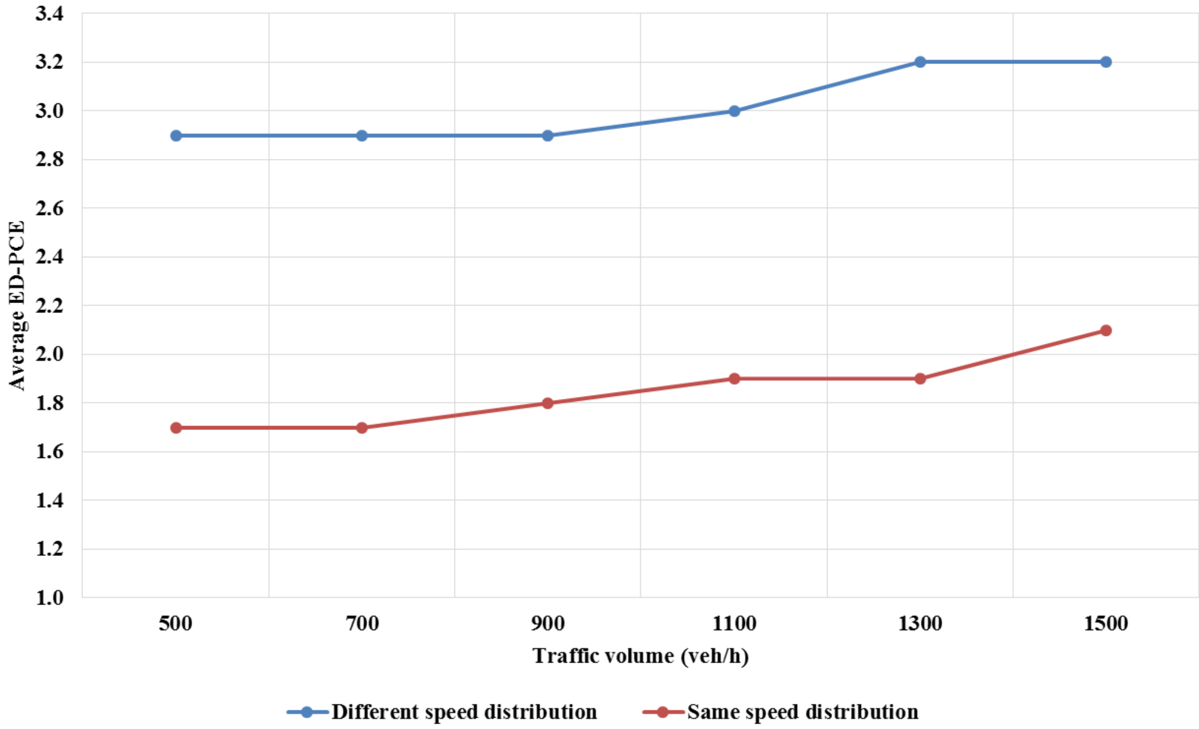

Figure 8.5 Average ED-PCEs for different traffic volume

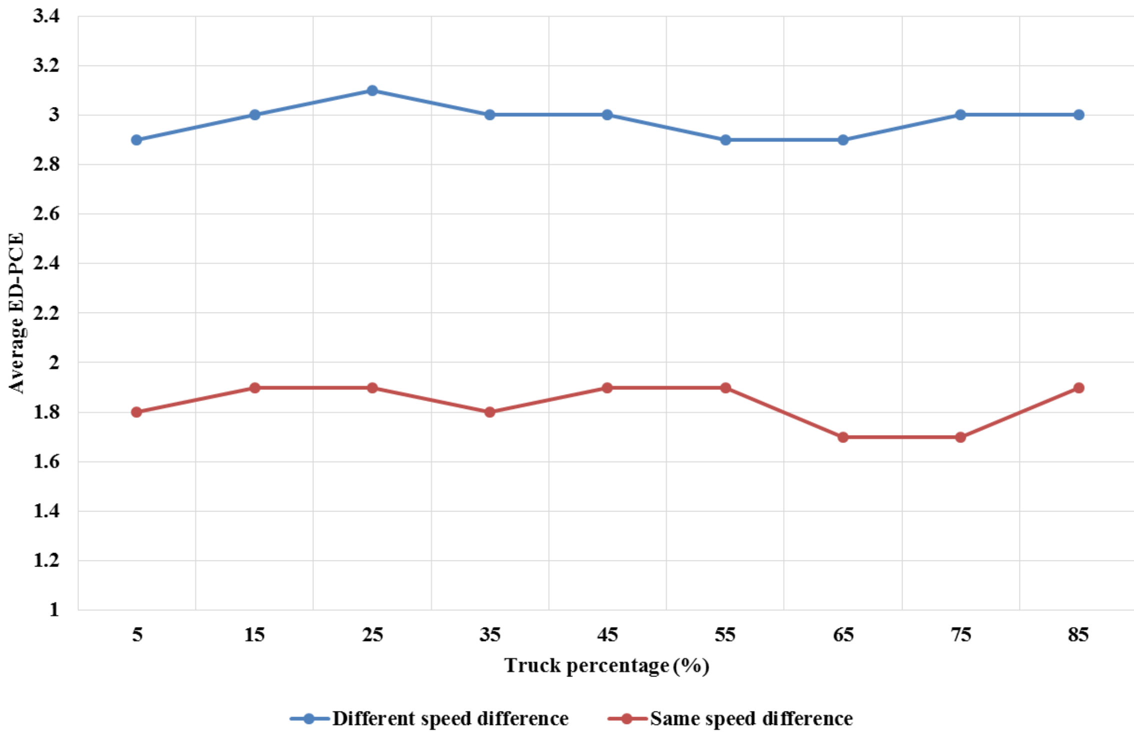

Figure 8.6 Average ED-PCEs for different truck percentage

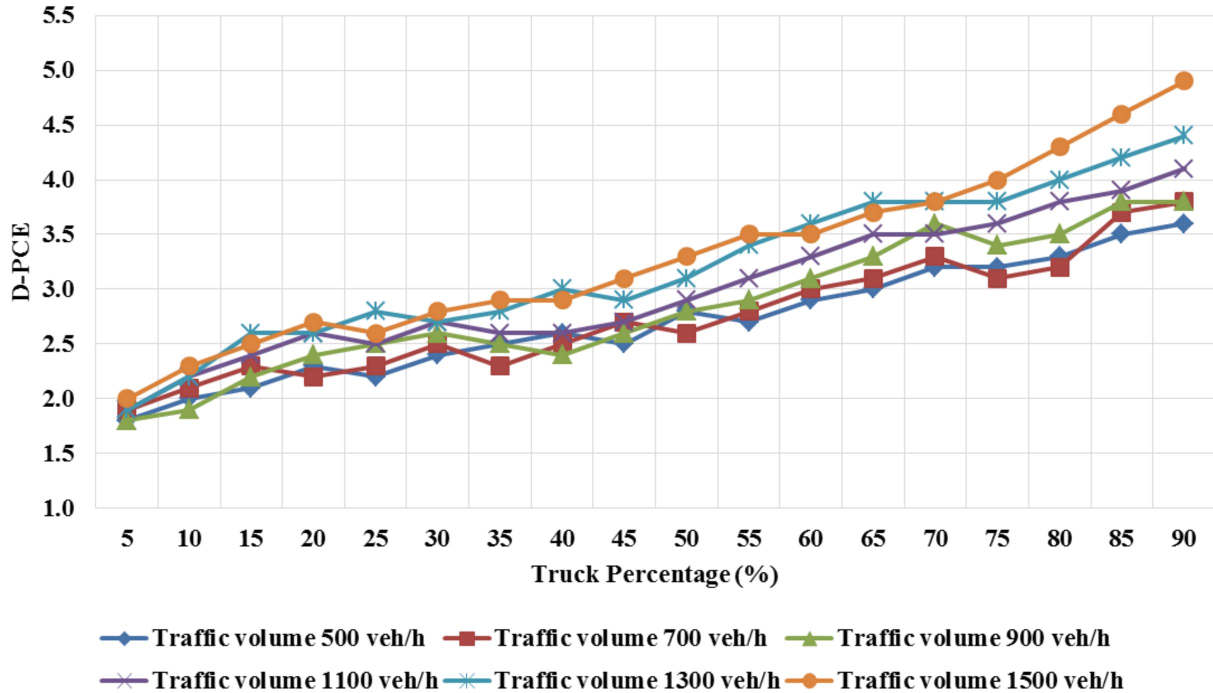

Figure 8.7 Results of D-PCEs

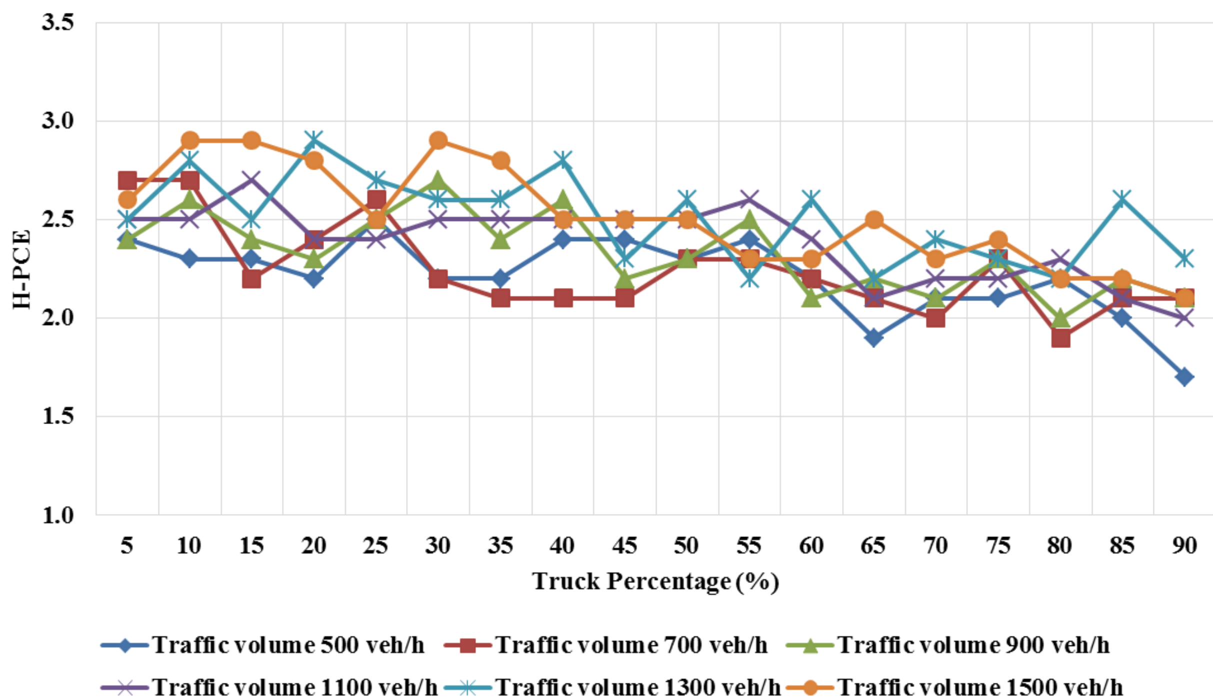

Figure 8.8 Results of H-PCEs for shoulder lane

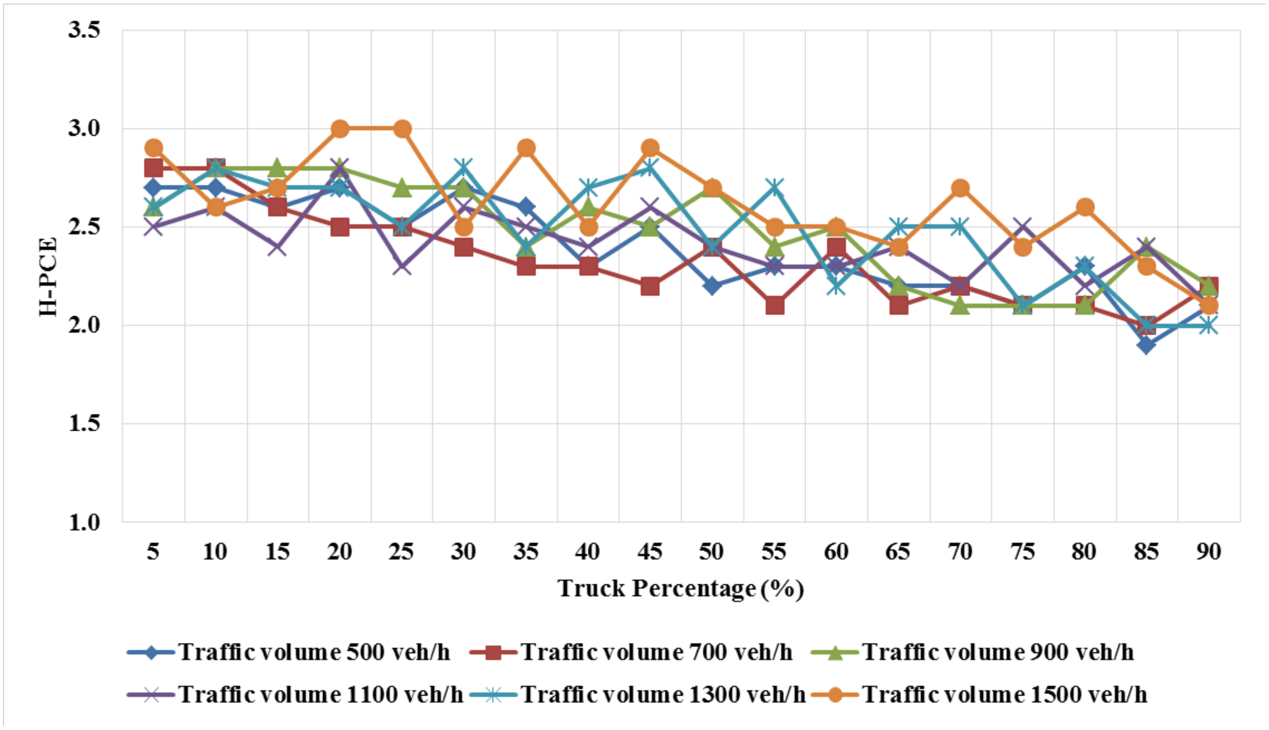

Figure 8.9 Results of H-PCEs for median lane

Chapter 9 PCE Analysis with Simulation Data under Truck Restriction Conditions

In this section, all trucks are set as restricted on shoulder lanes without overtaking other vehicles. The truck restriction is implemented by setting a “lane closure” for all trucks on all road links and connectors in the VISSIM model. Other parameters in the simulation model are not changed except for the “lane closure” setting, and the PCE determination methodologies are the same as that in section 8.2. The objective for determining PCEs under the truck restriction condition is to find how the effects of trucks on the operation of passenger vehicles would be changed if the truck restrictions were implemented on I-80 in western Nebraska.

9.1 Equal-density-based PCE

Under truck restriction conditions, the results of ED-PCEs for three and one speed distributions are shown in Table 9.1 and Table 9.2, respectively. The comparisons of ED-PCEs between Nebraska and truck restriction conditions for three and one speed distributions are shown in Figure 9.1 and Figure 9.2, respectively. Results show that, under the truck restriction condition, for three speed distributions, the ED-PCE value ranges from 1.1 to 2.1 with an average of 1.6, and the ED-PCE is not significantly affected by truck percentage, but significantly increases with traffic volume. For one speed distribution, the ED-PCE value ranges from 1.1 to 1.6 with an average of 1.3, which is significantly lower than it is for different speed distributions, and the ED-PCE significantly increases with traffic volume and truck percentage. The estimated ED-PCEs under the truck restriction condition are close to recommended values in HCM 2010. The comparison shows that ED-PCEs under the truck restriction condition is significantly lower than that for the Nebraska condition, indicating that by the equal-density method, the effects of trucks on passenger car operation would decrease if the truck restriction were implemented.

9.2 Delay-based PCE

Under the truck restriction condition, the results of D-PCEs are shown in Table 9.3. The comparisons of D-PCEs between Nebraska and the truck restriction condition are shown in Figure 9.3. Results show that, under the truck restriction condition, the D-PCE value ranges from 1.1 to 3.2 with an average of 1.5, and the D-PCE significantly increases with traffic volume and truck percentage. The estimated D-PCEs under the truck restriction condition are close to recommended values in the HCM 2010. The comparison shows that D-PCEs under the truck restriction condition is significantly lower than that for Nebraska conditions, indicating that for the delay-based method, the effects of trucks on passenger car operation would be decrease if the truck restriction were implemented.

9.3 Headway-based PCE

Under the truck restriction condition, the results of the H-PCEs for the shoulder lane and median lane are shown in Table 9.4. The comparisons of H-PCEs between Nebraska and the truck restriction condition for shoulder lanes and median lanes are shown in Figure 9.4 and Figure 9.5, respectively. Results show that, under the truck restriction condition, for the shoulder lane, the H-PCE value ranges from 1.1 to 1.7 with an average of 1.4, and the H-PCE is not significantly affected by traffic volume, but significantly decreases with an increase in truck percentage. For the median lane, the H-PCE value ranges from 1.1 to 1.9 with an average of 1.5, and the H-PCE significantly increases with traffic volume and decreases with an increase in truck percentage. The H-PCEs for the median lane is significantly higher than that for the shoulder lane. The estimated H-PCEs under the truck restriction condition are close to the recommended values in the HCM 2010. The comparison shows that H-PCEs under the truck restriction condition are significantly lower than that for the Nebraska condition, indicating that by the headway-based method, the effects of trucks on passenger car operation would be decreased if the truck restriction were implemented.

9.4 Concluding Remarks

In this chapter, the PCEs based on equal-density, delay, headway, and platoon methods under truck restriction conditions are calculated respectively using these simulation data. The PCEs under truck restriction conditions based on all methods except the platoon methods are significantly lower than the PCEs under Nebraska conditions, indicating that effects of trucks on passenger cars operation would be decrease if the truck restriction were implemented.

Table 9.1 ED-PCEs for truck restriction with three speed distributions

Traffic Volume (veh/h)	Truck Percentage (%)								
	5	15	25	35	45	55	65	75	85
500	1.4	1.7	1.4	1.5	1.6	1.4	1.2	1.5	1.4
700	1.1	1.3	1.5	1.6	1.5	1.2	1.3	1.3	1.2
900	1.3	1.5	1.5	1.3	1.7	1.3	1.5	1.7	1.5
1100	1.1	1.3	1.4	1.6	1.7	1.8	1.9	1.8	1.7
1300	1.4	1.6	1.7	1.9	1.8	1.8	1.6	1.5	1.9
1500	1.7	1.8	2.1	2.0	2.0	--	--	--	--

*Note: -- represents lacking adequate observations for this group.

Table 9.2 ED-PCEs for truck restriction with one speed distribution

Traffic Volume (veh/h)	Truck Percentage (%)								
	5	15	25	35	45	55	65	75	85
500	1.3	1.5	1.3	1.2	1.5	1.3	1.1	1.4	1.4
700	1.1	1.3	1.2	1.1	1.4	1.1	1.1	1.4	1.2
900	1.1	1.2	1.2	1.1	1.4	1.2	1.2	1.4	1.2
1100	1.1	1.3	1.3	1.2	1.4	1.4	1.3	1.2	1.4
1300	1.2	1.4	1.4	1.3	1.5	1.5	1.5	1.3	1.6
1500	1.4	1.5	1.6	1.5	1.6	--	--	--	--

*Note: -- represents lacking adequate observations for this group.

Table 9.3 D-PCEs for truck restriction conditions

Truck Percentage (%)	Traffic Volume (veh/h)					
	500	700	900	1100	1300	1500
5	1.2	1.3	1.3	1.4	1.4	1.3
10	1.3	1.4	1.3	1.4	1.4	1.4
15	1.3	1.2	1.2	1.4	1.4	1.4
20	1.2	1.2	1.4	1.4	1.4	1.4
25	1.2	1.3	1.2	1.4	1.5	1.4
30	1.2	1.2	1.3	1.5	1.6	1.4
35	1.1	1.3	1.4	1.5	1.4	1.5
40	1.3	1.3	1.2	1.6	1.5	1.5
45	1.2	1.4	1.4	1.4	1.5	1.5
50	1.3	1.4	1.4	1.6	1.7	1.6
55	1.4	1.4	1.5	1.5	1.6	1.7
60	1.4	1.4	1.4	1.5	1.7	1.8
65	1.4	1.4	1.5	1.6	1.8	2
70	1.4	1.5	1.6	1.7	1.8	2
75	1.5	1.5	1.6	1.8	1.8	2.4
80	1.6	1.6	1.6	1.8	1.9	2.7
85	1.5	1.7	1.7	1.8	1.9	3
90	1.7	1.8	1.8	2.2	1.8	3.2

Table 9.4 H-PCEs for truck restriction conditions

Lane	Truck Percentage (%)	Traffic Volume (veh/h)					
		500	700	900	1100	1300	1500
Shoulder Lane	5	1.5	1.7	1.6	1.6	1.6	1.7
	10	1.7	1.6	1.7	1.7	1.7	1.6
	15	1.7	1.6	1.6	1.6	1.6	1.6
	20	1.5	1.6	1.6	1.6	1.6	1.6
	25	1.5	1.5	1.5	1.5	1.5	1.5
	30	1.5	1.5	1.4	1.4	1.4	1.5
	35	1.3	1.4	1.4	1.4	1.4	1.4
	40	1.3	1.3	1.4	1.3	1.3	1.3

	45	1.3	1.3	1.3	1.3	1.3	1.3
	50	1.2	1.3	1.3	1.2	1.3	1.3
	55	1.2	1.2	1.2	1.3	1.3	1.3
	60	1.3	1.2	1.3	1.3	1.3	1.3
	65	1.2	1.2	1.2	1.4	1.3	1.2
	70	1.3	1.2	1.3	1.4	1.3	1.2
	75	1.3	1.3	1.3	1.3	1.3	1.3
	80	1.1	1.3	1.3	1.3	1.4	1.3
	85	1.3	1.4	1.2	1.4	1.4	1.5
	90	1.3	1.4	1.6	1.4	1.5	1.4
Median Lane	5	1.7	1.6	1.7	1.7	1.8	1.9
	10	1.7	1.6	1.7	1.6	1.7	1.9
	15	1.6	1.6	1.6	1.6	1.7	1.8
	20	1.7	1.5	1.6	1.6	1.7	1.8
	25	1.6	1.5	1.6	1.6	1.7	1.7
	30	1.6	1.5	1.6	1.6	1.7	1.7
	35	1.5	1.4	1.5	1.6	1.6	1.7
	40	1.5	1.4	1.5	1.5	1.6	1.7
	45	1.4	1.4	1.5	1.4	1.6	1.6
	50	1.4	1.4	1.4	1.4	1.5	1.6
	55	1.4	1.3	1.4	1.4	1.5	1.6
	60	1.4	1.3	1.4	1.3	1.5	1.6
	65	1.4	1.3	1.4	1.3	1.5	1.5
	70	1.3	1.2	1.3	1.3	1.4	1.5
	75	1.3	1.1	1.2	1.3	1.4	1.5
	80	1.3	1.3	1.3	1.4	1.4	1.5
	85	1.4	1.4	1.4	1.5	1.6	1.6
	90	1.4	1.5	1.5	1.6	1.6	1.5

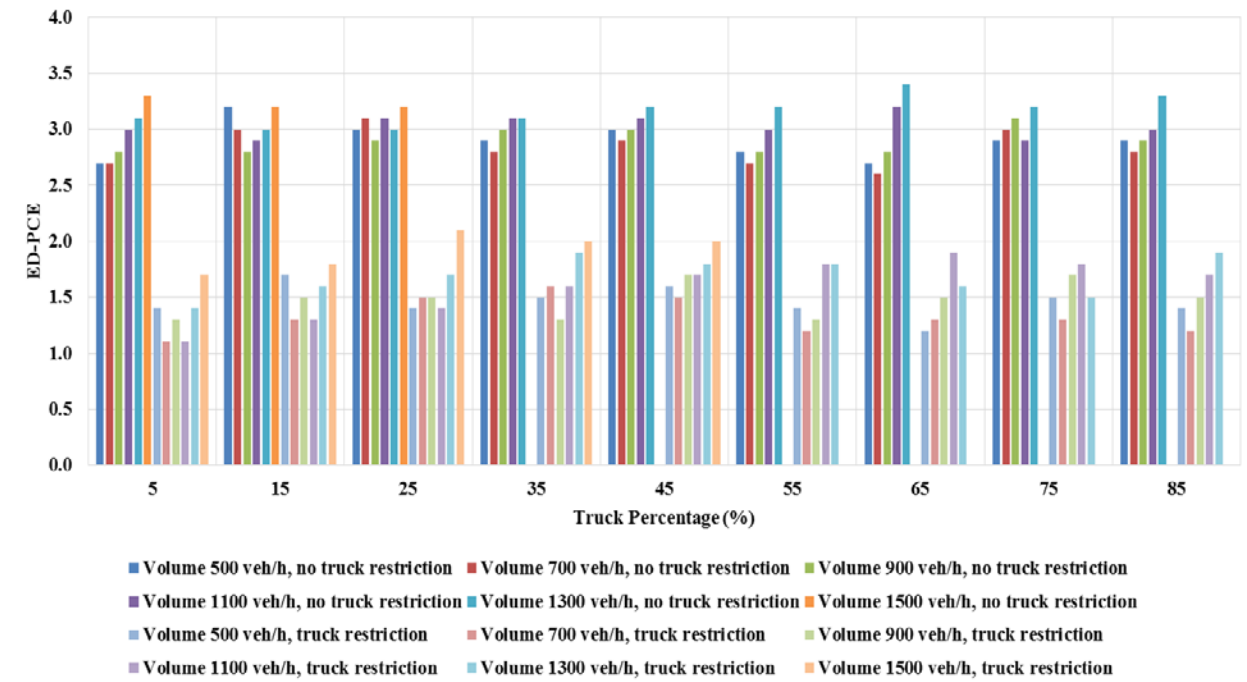

Figure 9.1 Comparison of ED-PCEs between Nebraska/truck restrictions condition at three speed distributions

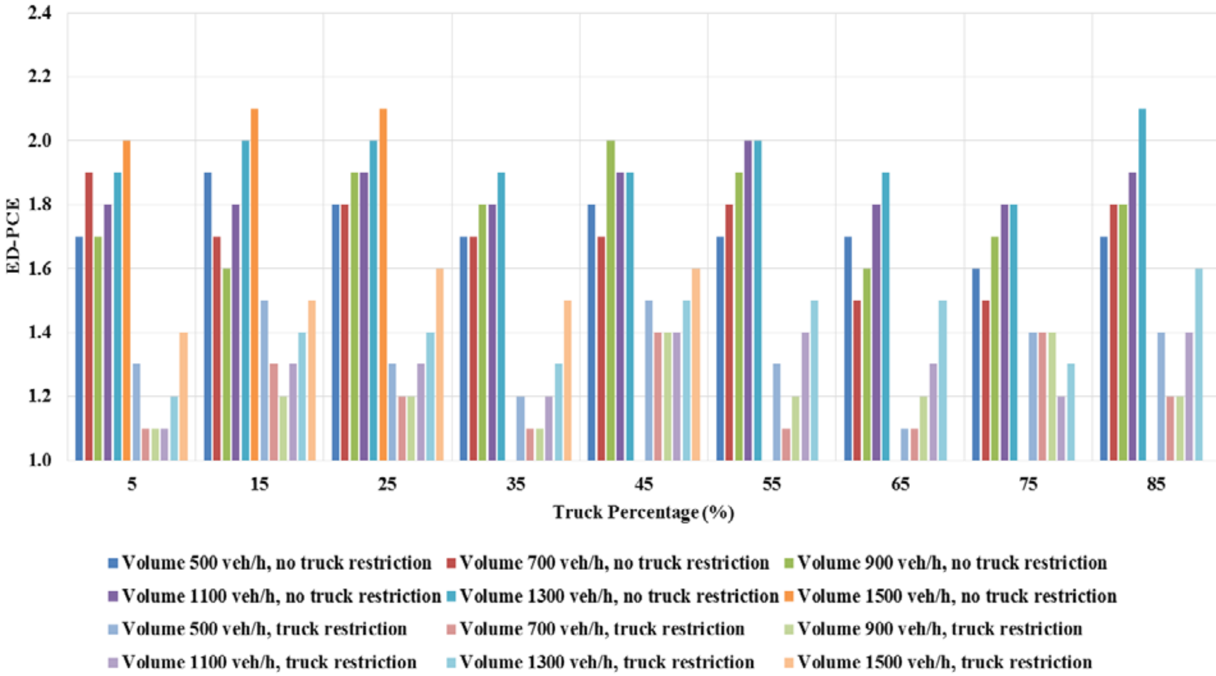

Figure 9.2 Comparison of ED-PCEs between Nebraska/truck restrictions condition at one speed distribution

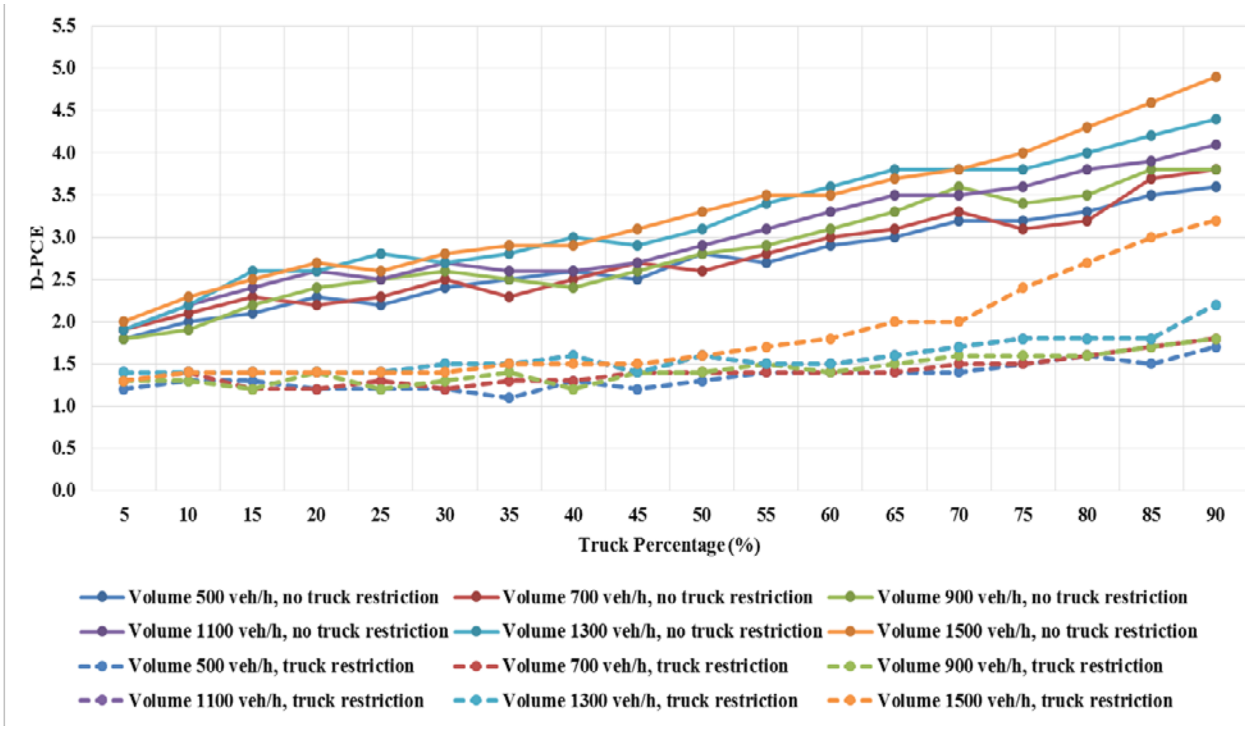

Figure 9.3 Comparison of D-PCEs between Nebraska/truck restriction conditions

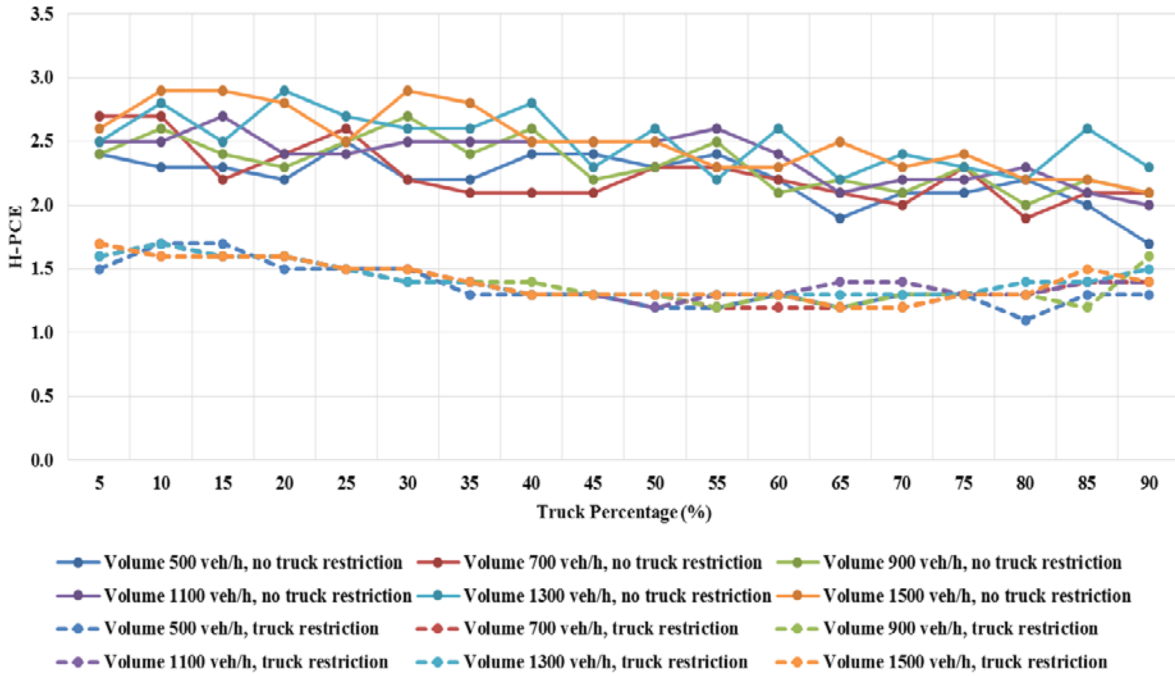

Figure 9.4 Comparison of H-PCEs between Nebraska/truck restriction conditions for shoulder lane

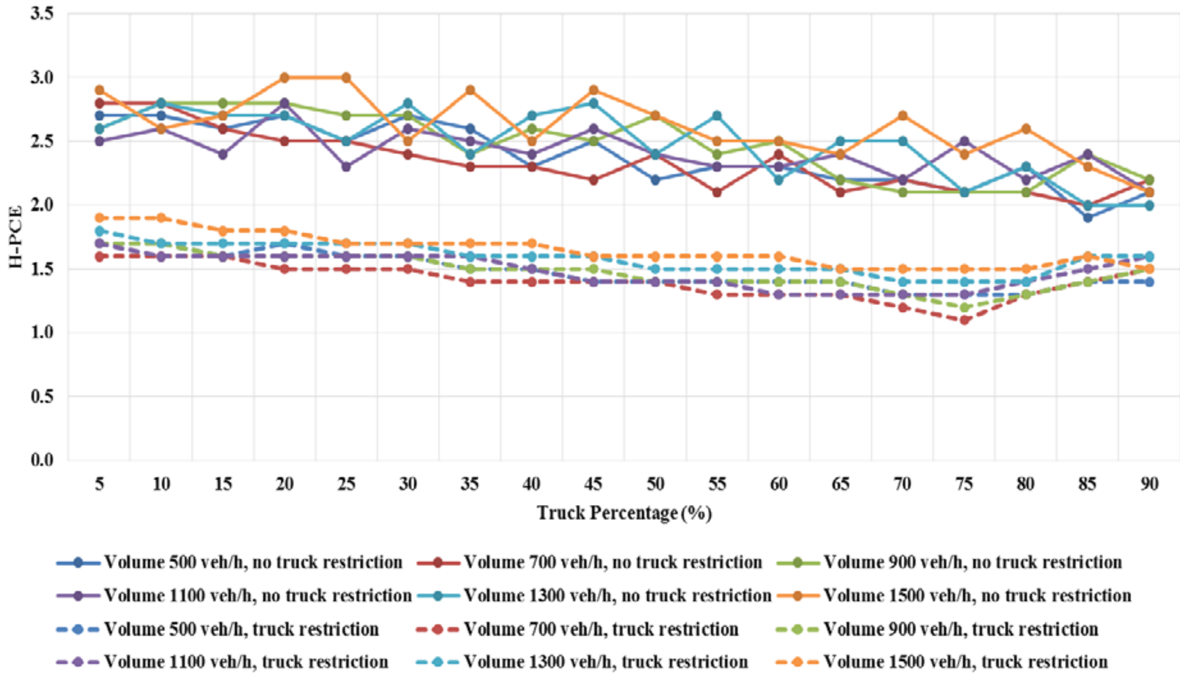

Figure 9.5 Comparison of H-PCEs between Nebraska/truck restriction conditions for median lane

Chapter 10 Concluding Remarks

10.1 Conclusions

This research explores the passenger car equivalents (PCE) at high truck percentage conditions on I-80 in Nebraska. The PCEs are calculated by equal-density (ED-PCE), delay-based (D-PCE), and headway-based (H-PCE). The conclusions are discussed below.

1. The results of the preliminary analysis show that approximately 30% of the vehicles in the traffic flow on I-80 are trucks. A lower truck percentage occurs periodically east of Grand Island where traffic volumes are higher. Vice versa, a higher truck percentage occurs periodically west of Grand Island where traffic volumes are lower. The average speed of trucks is 7.1 mph, which is significantly lower than passenger cars, but the speed of a single-unit and heavy trucks are close to each other.

2. In the HCM analysis, the speed-volume relationship based on empirical data shows that, for I-80 in Nebraska, although the level of service is at level A or B according to traffic volume and density, the operating speeds are lower than those predicted by the FFS curve in the HCM. These speeds correspond to a LOS at C or D. The vehicles may be affected by the existence of platoons, and the PCEs may be underestimated in the HCM 2010.

3. The results of the platoon analysis shows that approximately 90% of vehicles are caught in a platoon, and approximately 50% of vehicles are classified as impeded vehicles. The average speeds of both cars and trucks as impeded vehicles are significantly lower than as non-impeded vehicles, which indicates that platoons may cause an increase for travel time and delay for vehicles.

The results of the platoon characteristic analysis show that, on average, vehicles impeded in platoons led by two trucks experience the highest speed reduction, degree of congestion, and platoon delay, compared with other platoon types. The platoons led by two trucks have the longest platoon length, existence time, and distance. If vehicles are impeded in platoons led by two trucks, the vehicles are most severely affected by platoons.

4. The results of PCEs under the Nebraska traffic condition based on empirical and simulation data are summarized in Table 10.1. The results show that the ED-PCEs, D-PCEs, and H-PCEs are higher than the recommended value in the HCM 2010. The affecting factor analysis shows that: 1) all of these PCEs significantly increase traffic volume; 2) the D-PCEs significantly increase with truck percentage, but the H-PCEs decrease with an increase in truck percentage; and 3) the H-PCEs for the median lane are significantly higher than for the shoulder lane. Also, the average ED-PCE based on the same speed distribution is 1.8, which is close to the value in the HCM 2010; the average ED-PCE based on a different (empirical) speed distribution is 3.0, which is much higher than the value in the HCM 2010. Thus, the underestimate of the ED-PCE in the HCM 2010 may be attributed to the same speed assumptions.

5. The results of PCEs under the simulated truck restriction condition are summarized in Table 10.2. The PCEs based on all determination methods are significantly lower than PCEs under the Nebraska condition, indicating that the effects of trucks on passenger car operation would be decreased if the truck restriction were implemented.

10.2 Recommendations

Based on the research results, the following recommendations are proposed.

1. The PCEs in the HCM 2010 for level freeway segments (1.5) may not be suitable for traffic flow on I-80 in western Nebraska. When using the equal-density-based simulation method to generate PCE values, the different speed distribution, instead of the same speed distribution for different vehicle classifications, should be used as input data.

2. According to the range of values, ED-PCE, D-PCE, and H-PCE are reasonable, as expected. However, due to the tendency that H-PCEs significantly decrease with an increase in truck percentage appears to be counteractive to the hypothesis that vehicles are affected more seriously when in a platoon led by a truck at high truck percentage conditions. The ED-PCEs based on the different speed distribution with an average of 3.0, and the D-PCEs with an average of 2.8 are finally recommended.

3. Due to the relative lower PCEs under the truck restriction condition, some traffic control measures, such as restricting trucks on the shoulder lane, or banning trucks using the median lane to overtake other vehicles, could be implemented at specific freeway segments with a high traffic volume and a high truck percentage to reduce the effects of trucks and platoons on passenger car operation.

Table 10.1 Summary of PCE determination for all methods under Nebraska traffic condition

PCE determination method	Range based on empirical data	Range based on simulation data	Affecting factors
ED-PCE (different speed distribution)	-	2.6~3.4	+ traffic volume
ED-PCE (same speed distribution)	-	1.5~2.1	+ traffic volume
D-PCE	-	1.8~4.9	+ traffic volume, + truck percentage
H-PCE	2.1~2.5	1.7~3.1	+ traffic volume, - truck percentage, median > shoulder

*Note: - means lacking observation.

Table 10.2 Summary of PCE determination for all methods under truck restriction condition

PCE determination method	Range based on simulation data	Affecting factors
ED-PCE (different speed distribution)	1.1~2.1	+ traffic volume
ED-PCE (same speed distribution)	1.1~1.6	+ traffic volume, + truck percentage
D-PCE	1.1~3.2	+ traffic volume, + truck percentage
H-PCE	1.1~1.9	+ traffic volume (only for median lane), - truck percentage, median > shoulder

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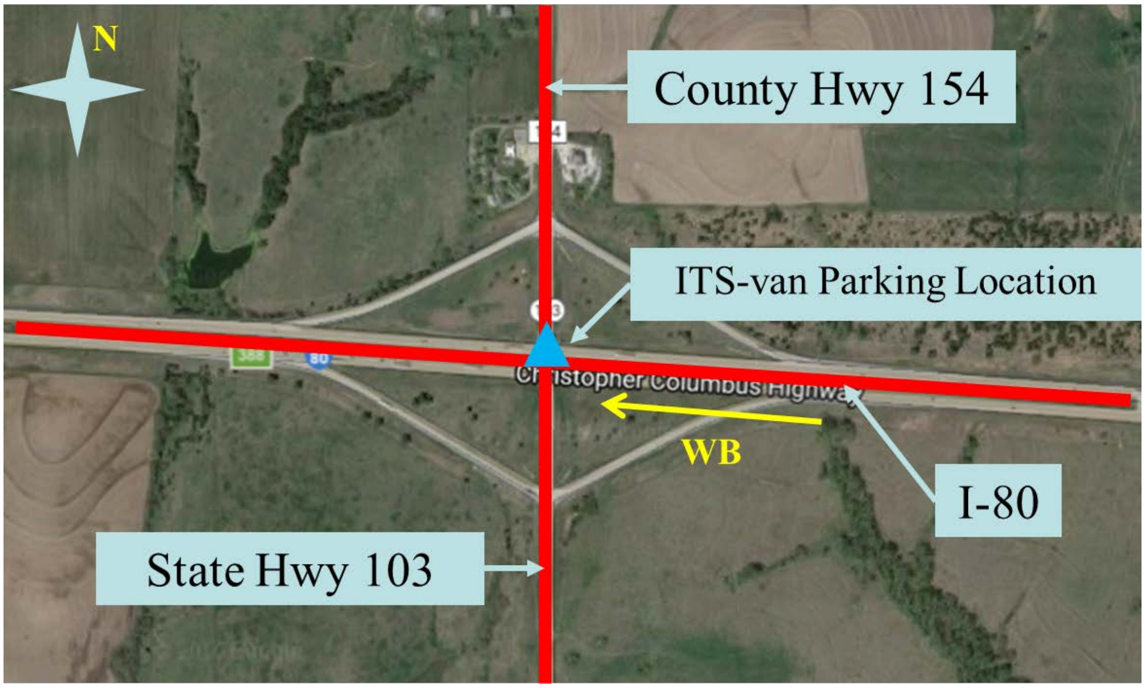
Appendix A: Data Collection Sites



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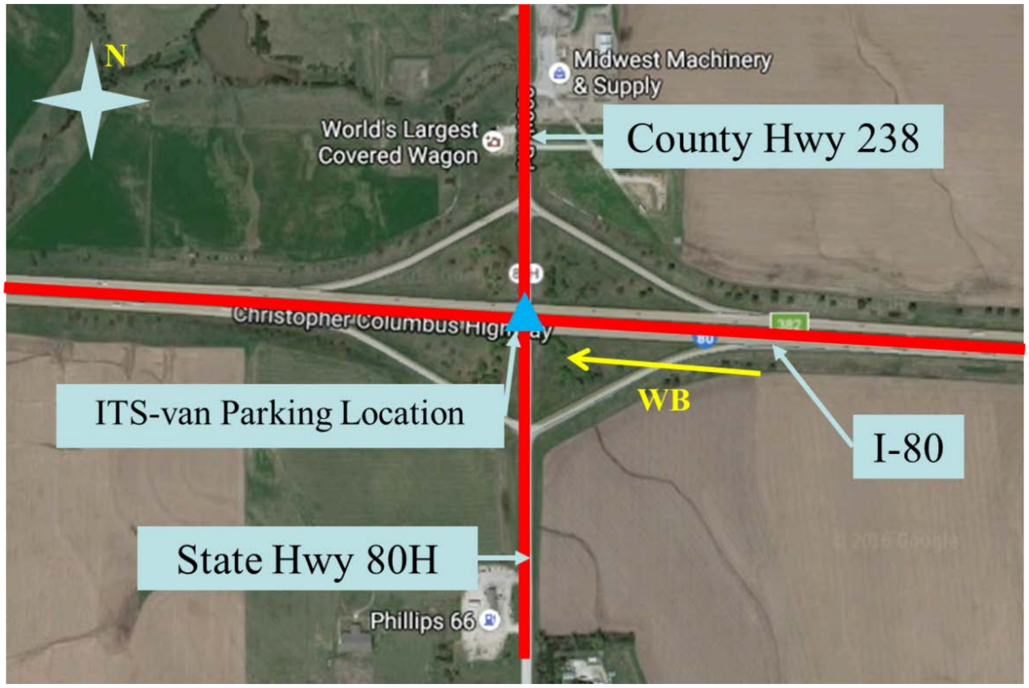

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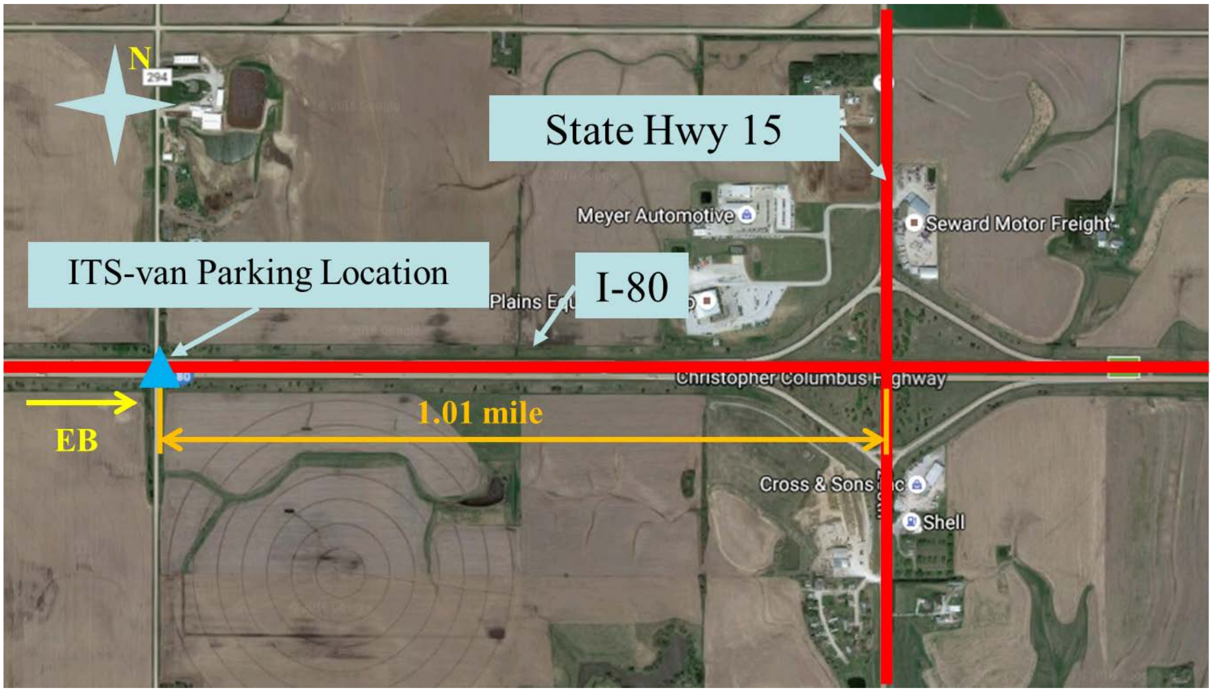
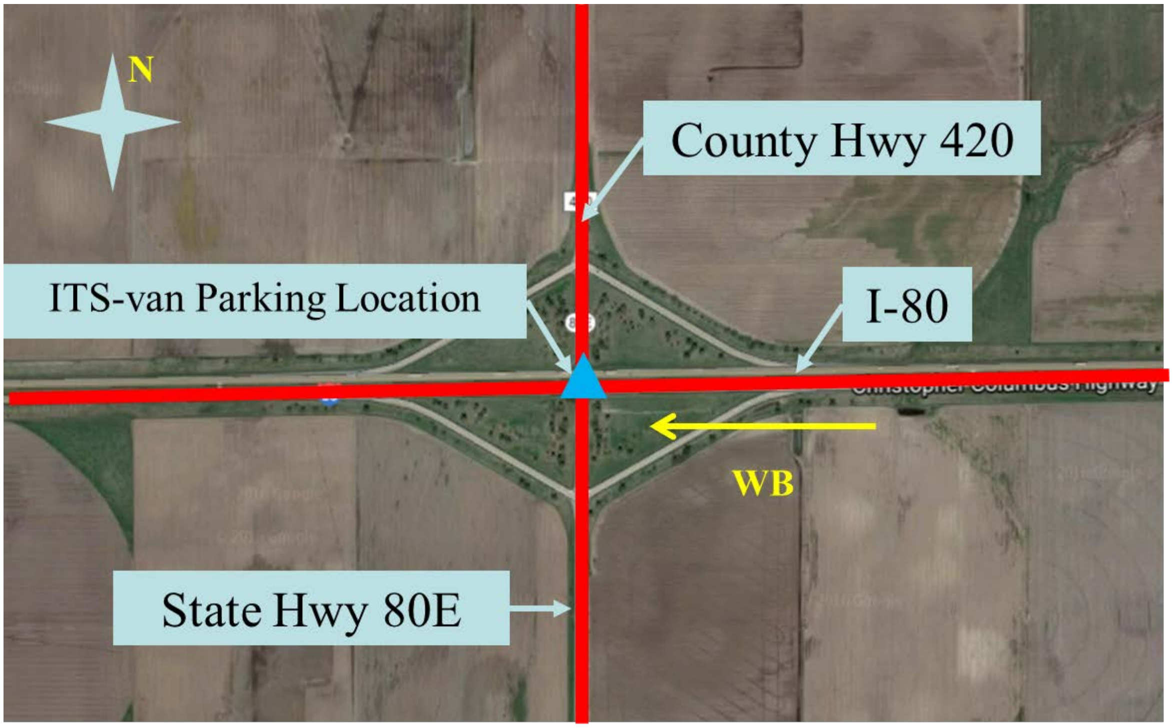


(c) Seward



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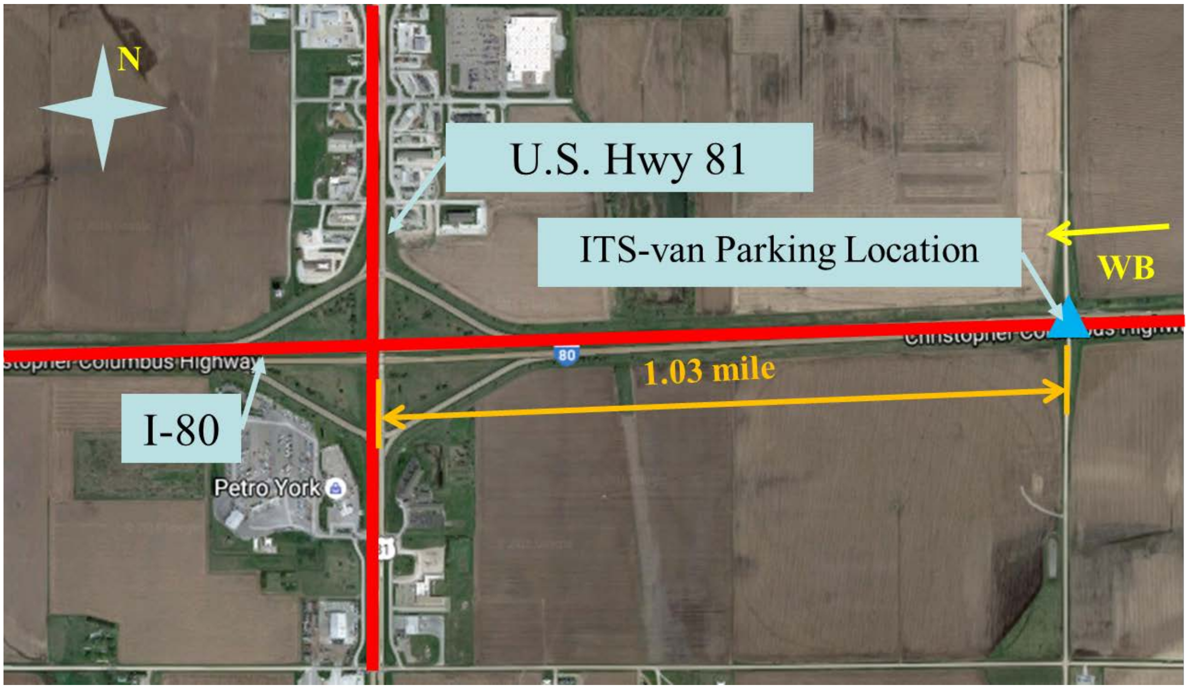
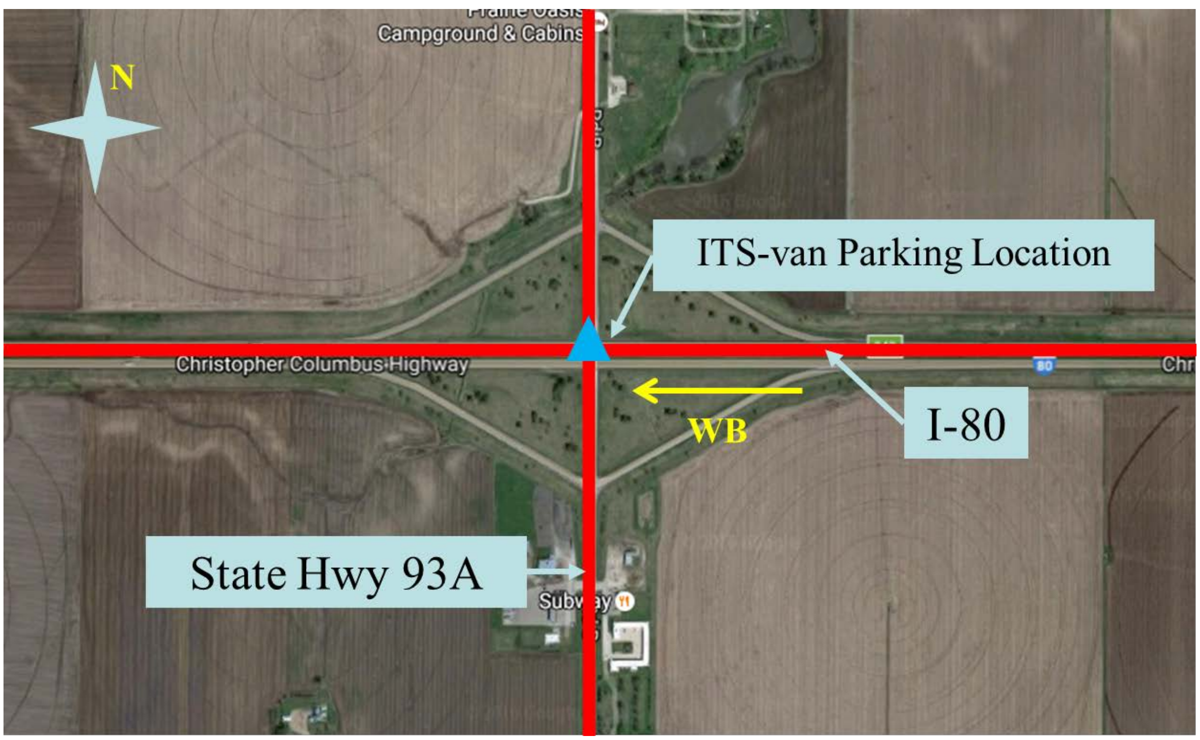
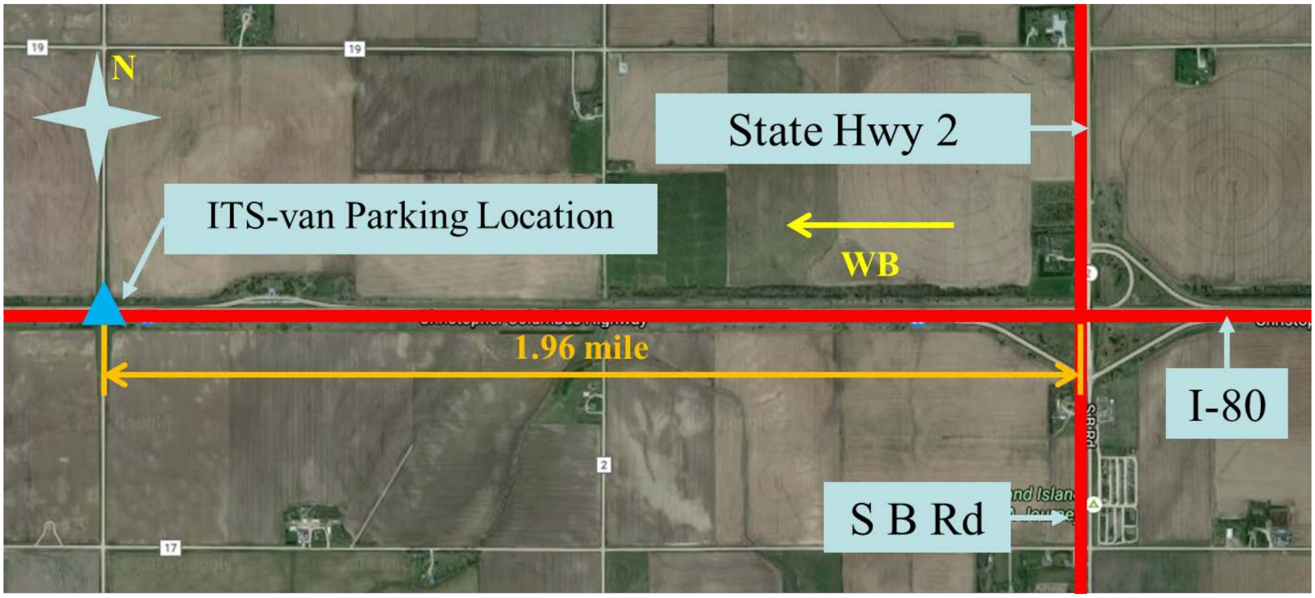


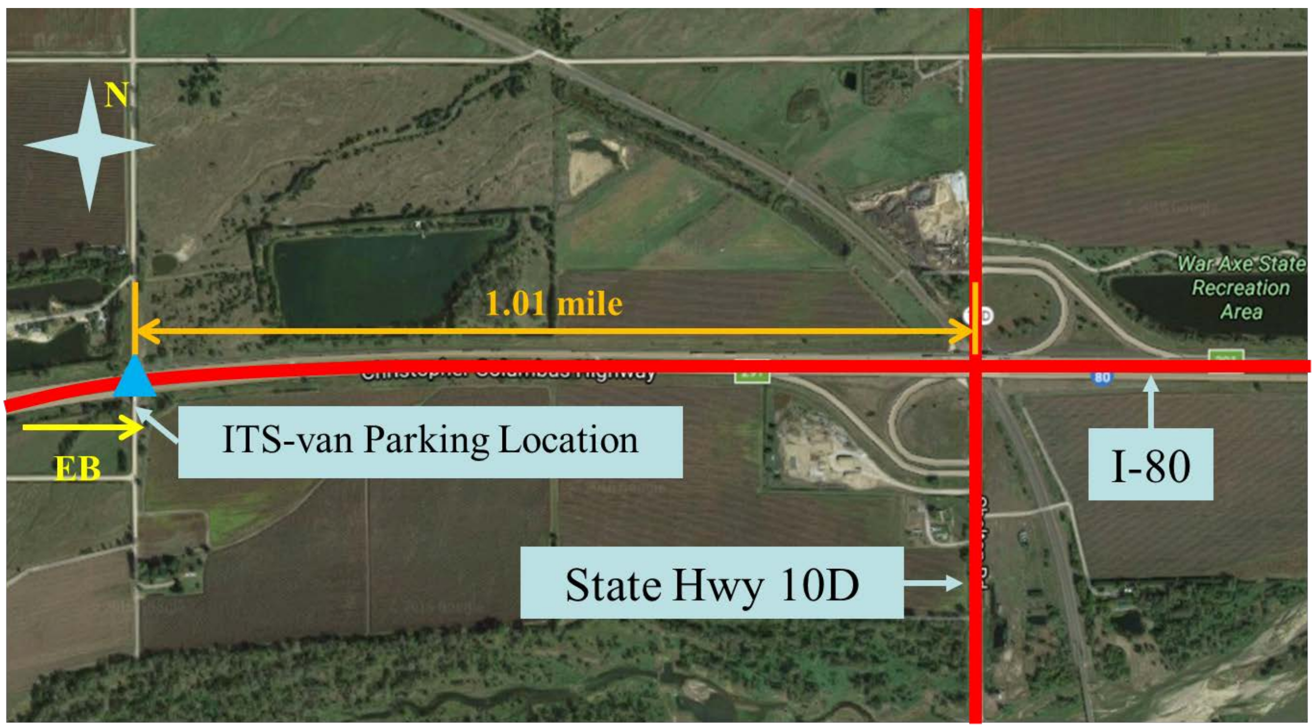
(e) York



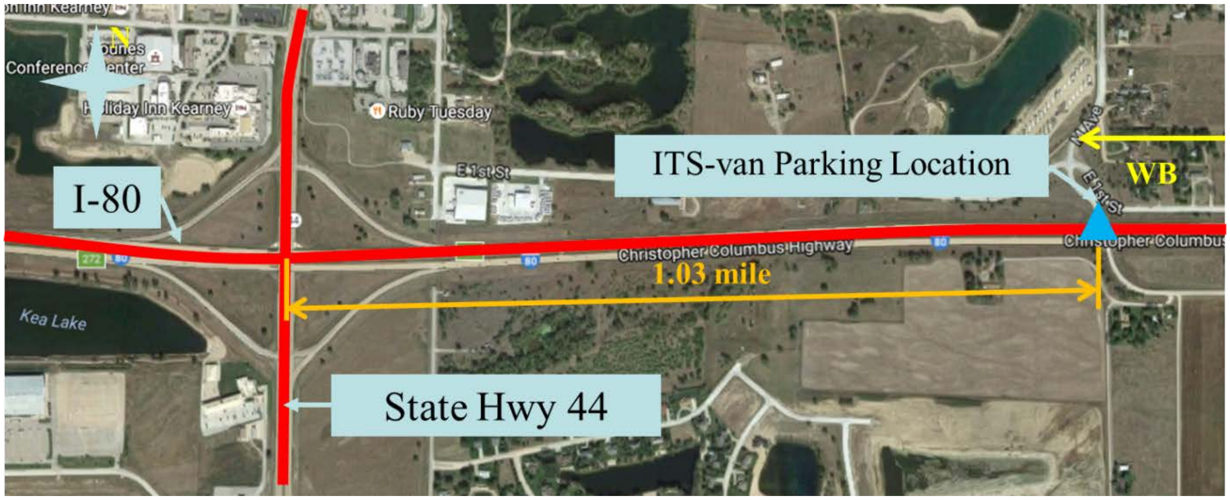
(f) Henderson



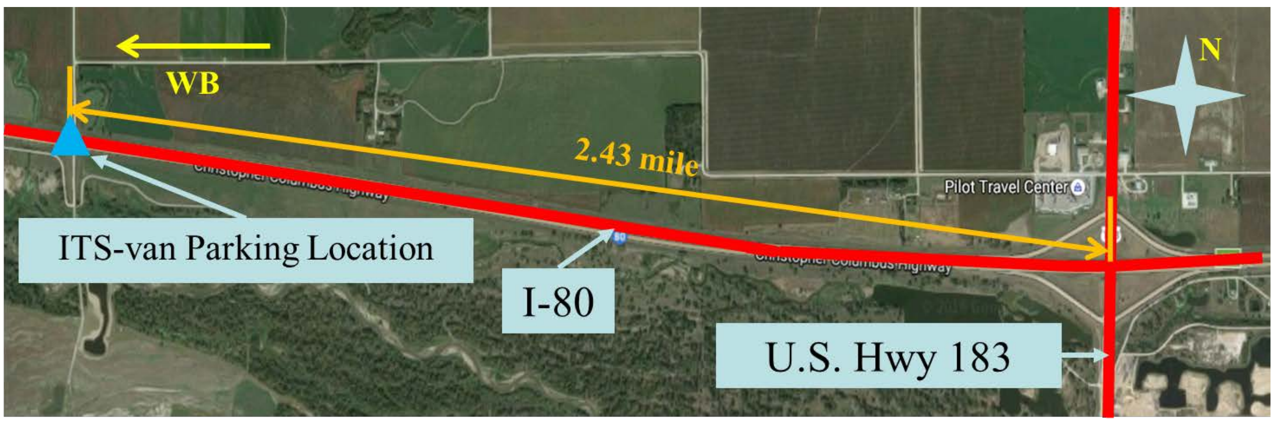
(g) Grand Island



(h) Shelton



(i) Kearney



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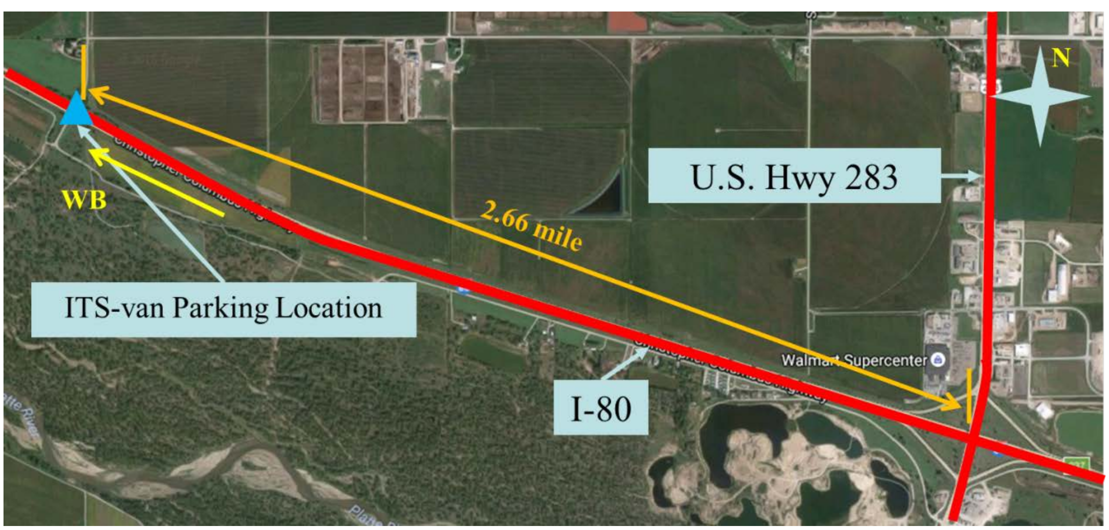

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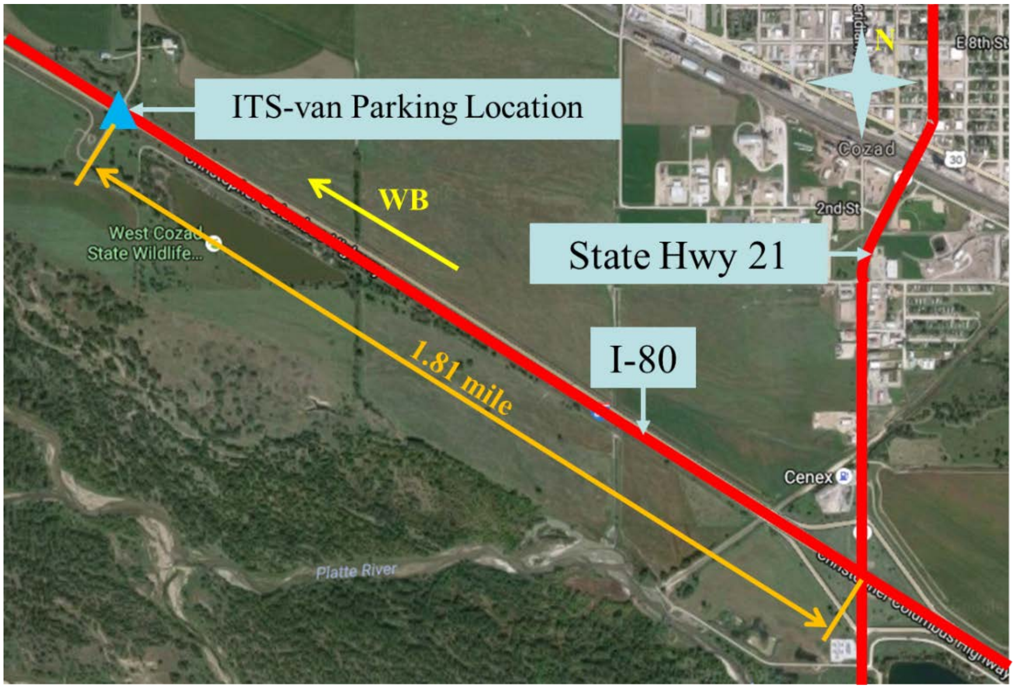
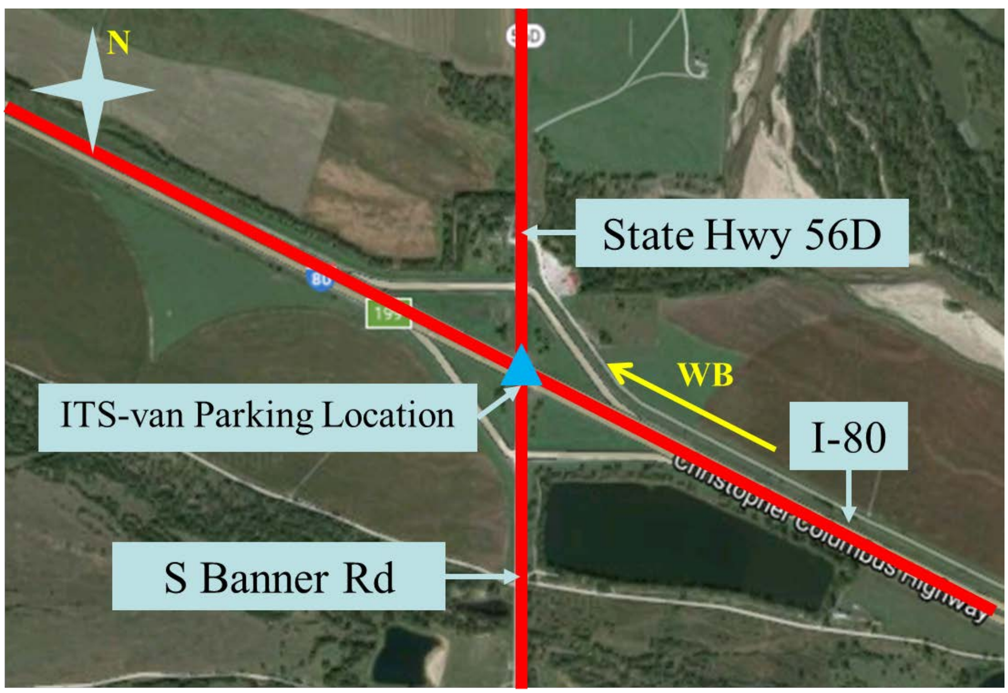
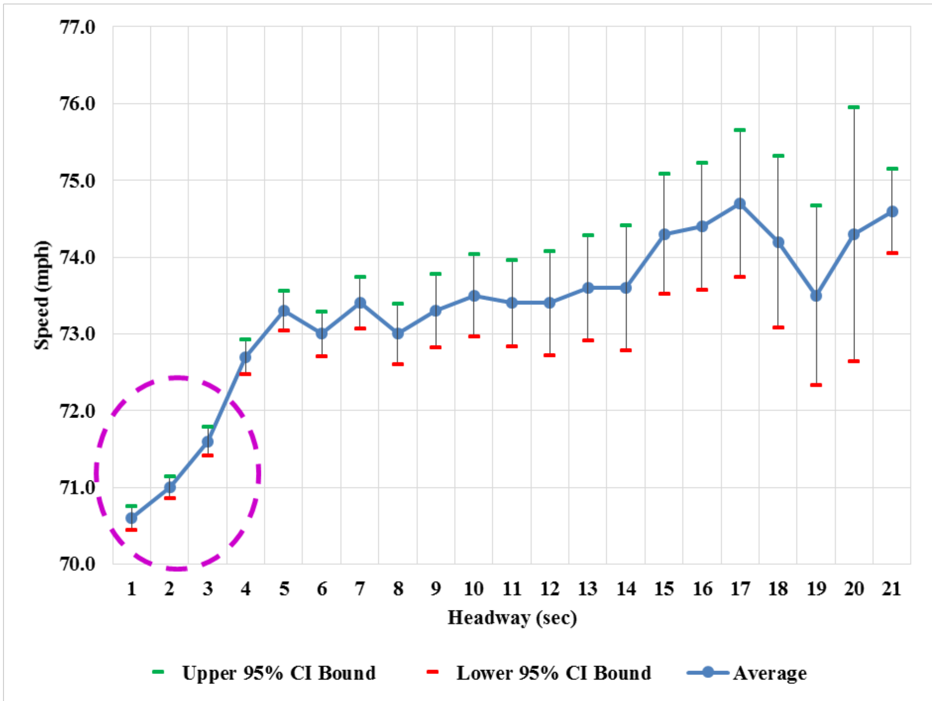


(l) Cozad



(m)Brady

Appendix B: Relationship for Average Speed and Headway for Different Headway Type



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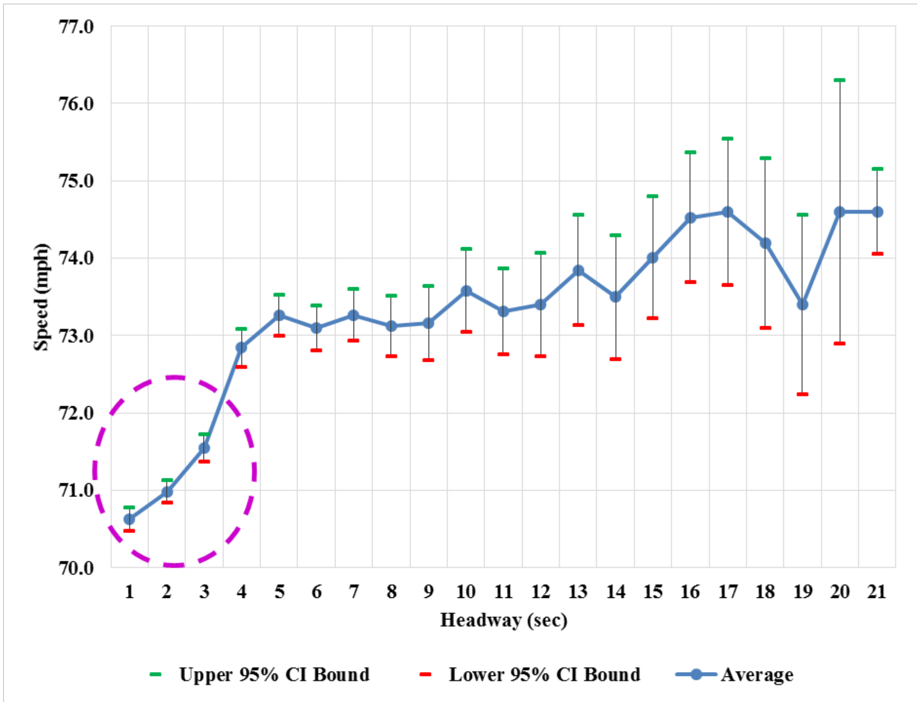
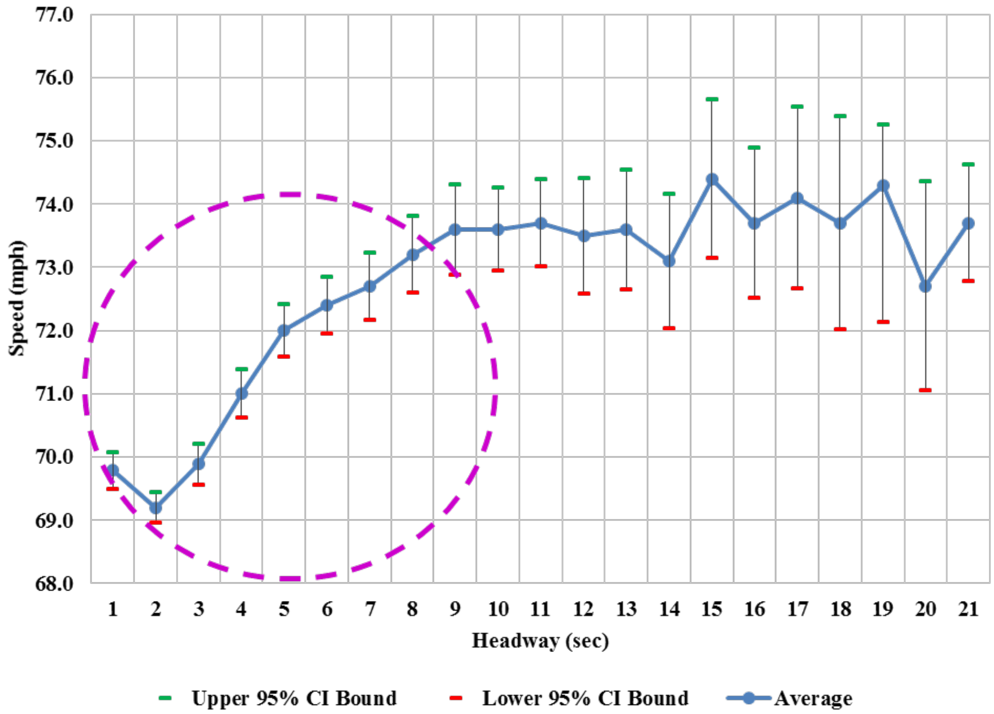


(b) cc-lagging headway



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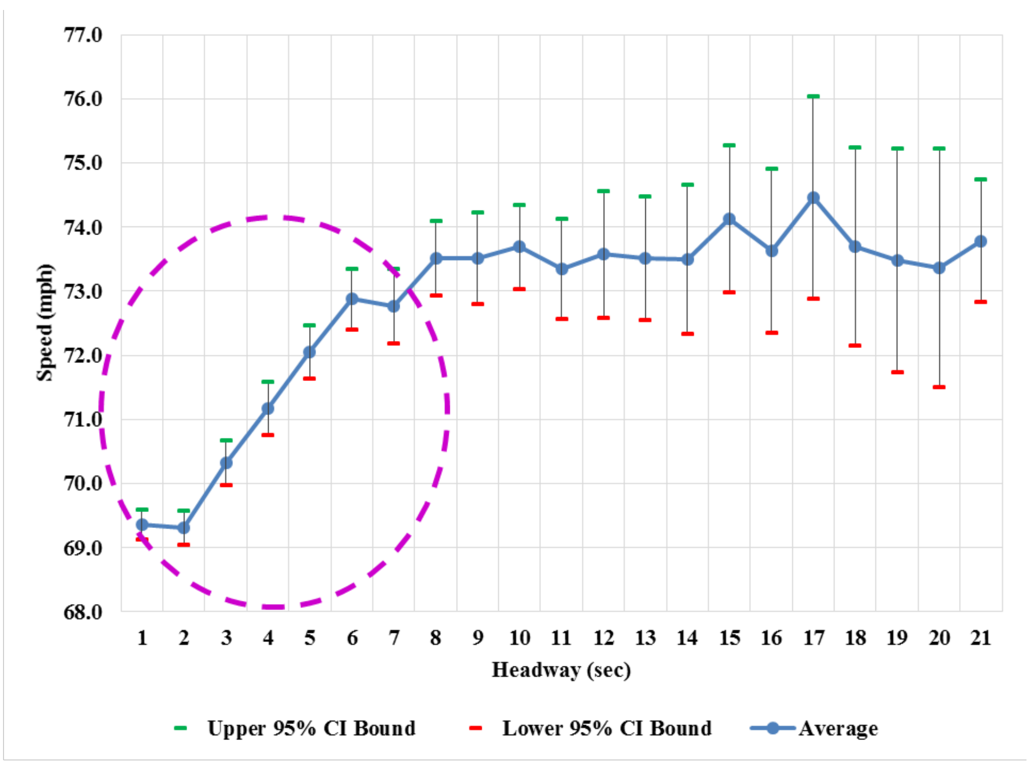
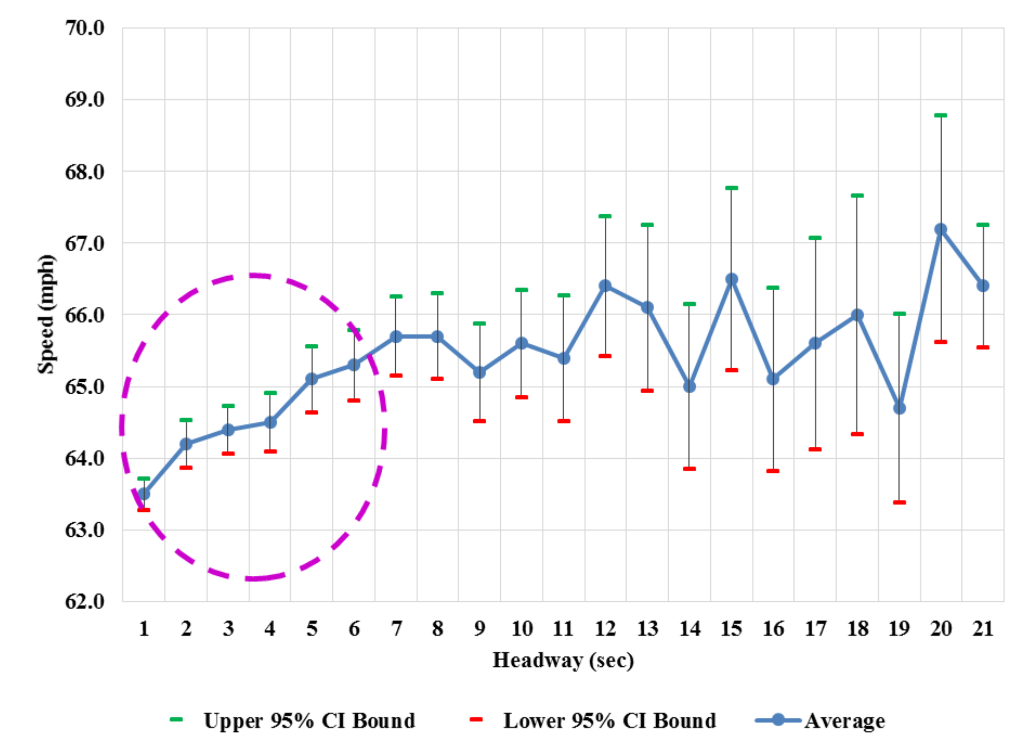
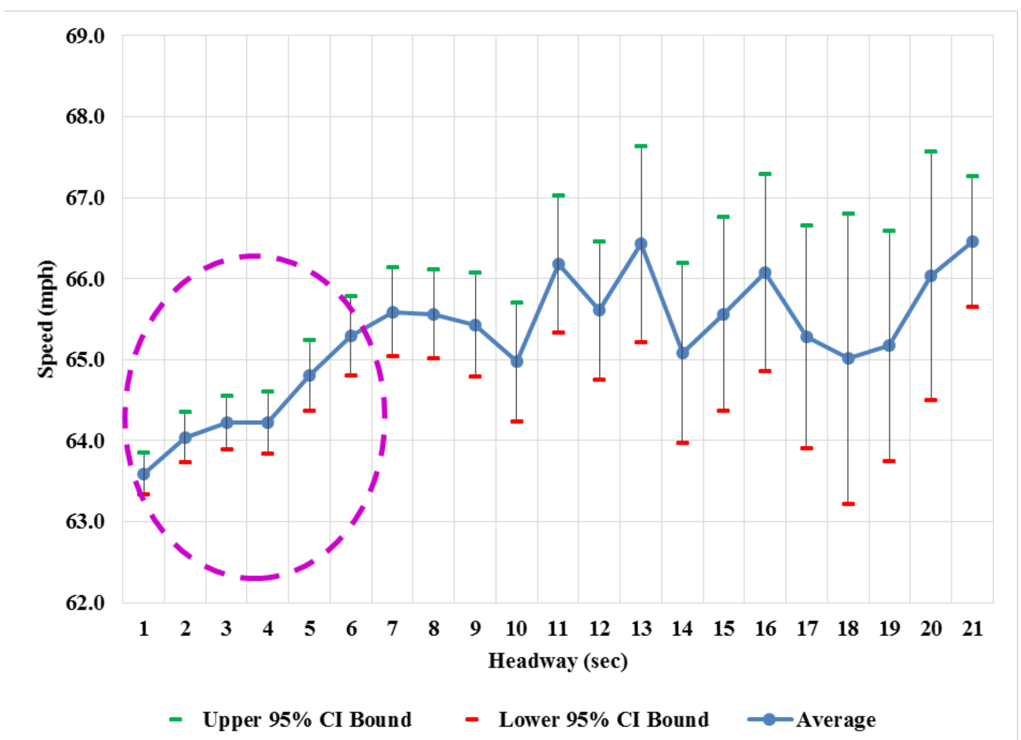


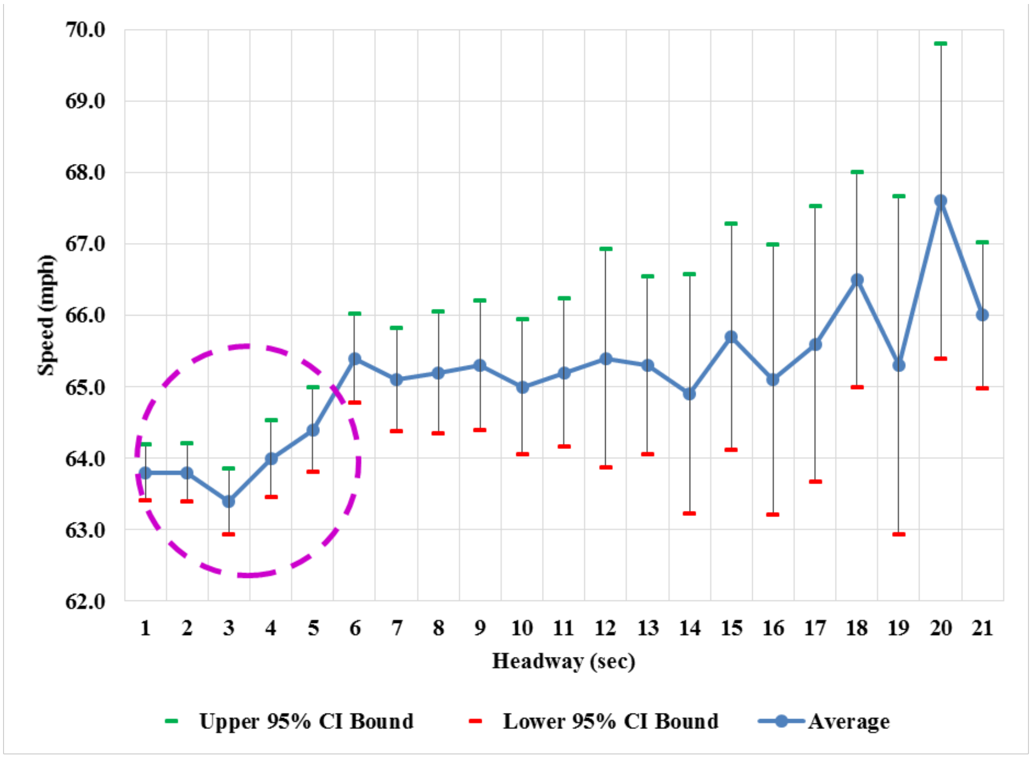
(d) ct-lagging headway



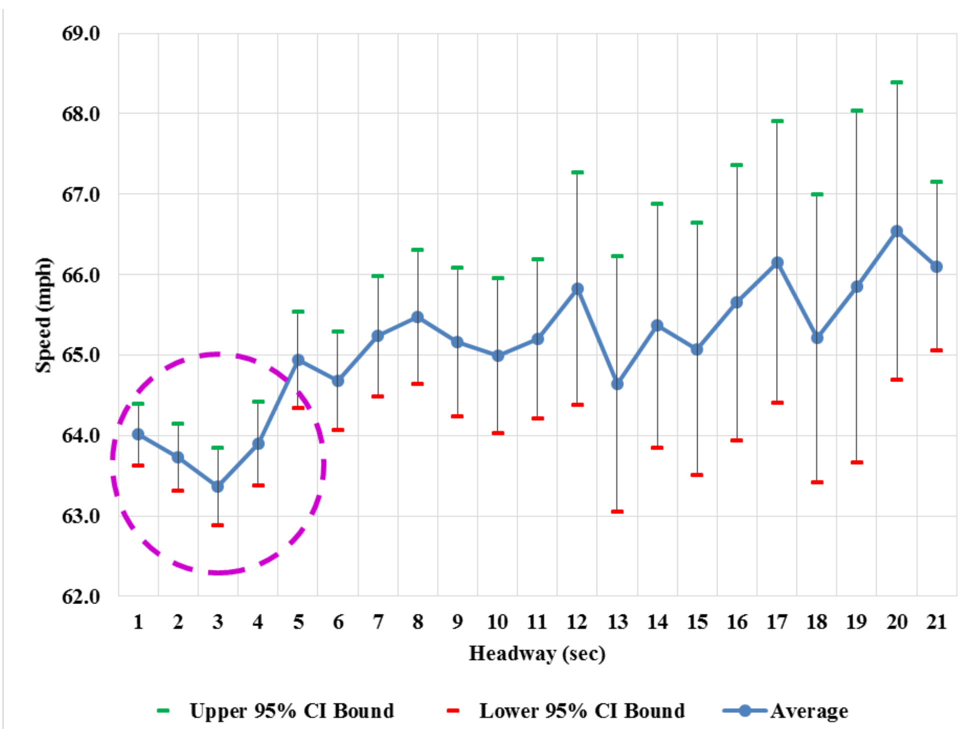
(e) tc-leading headway



(f) tc-lagging headway

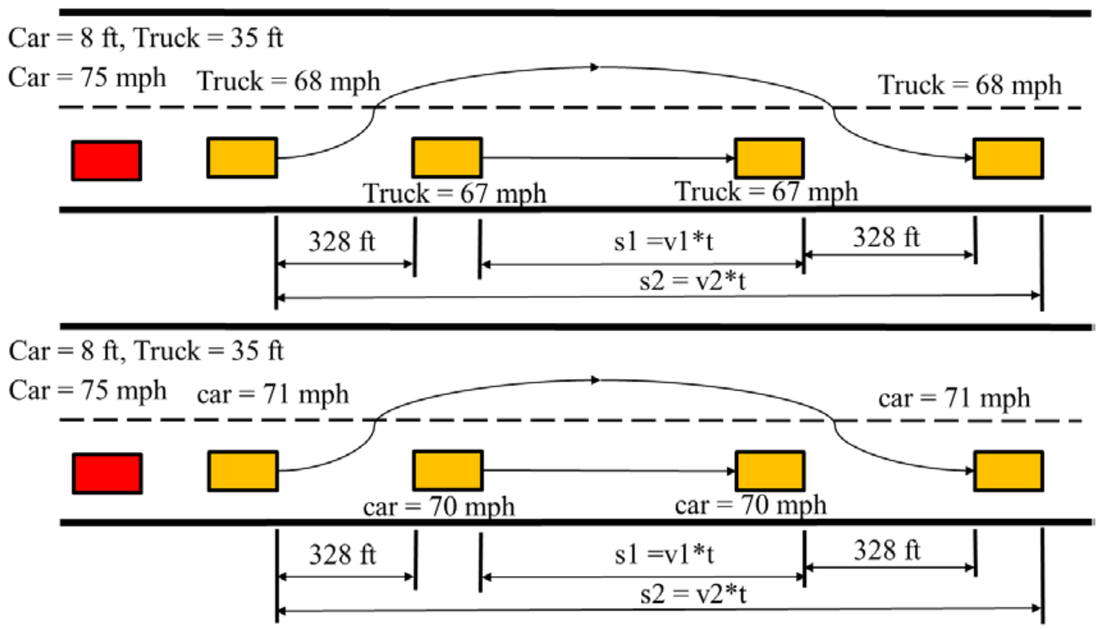


(g) tt-leading headway

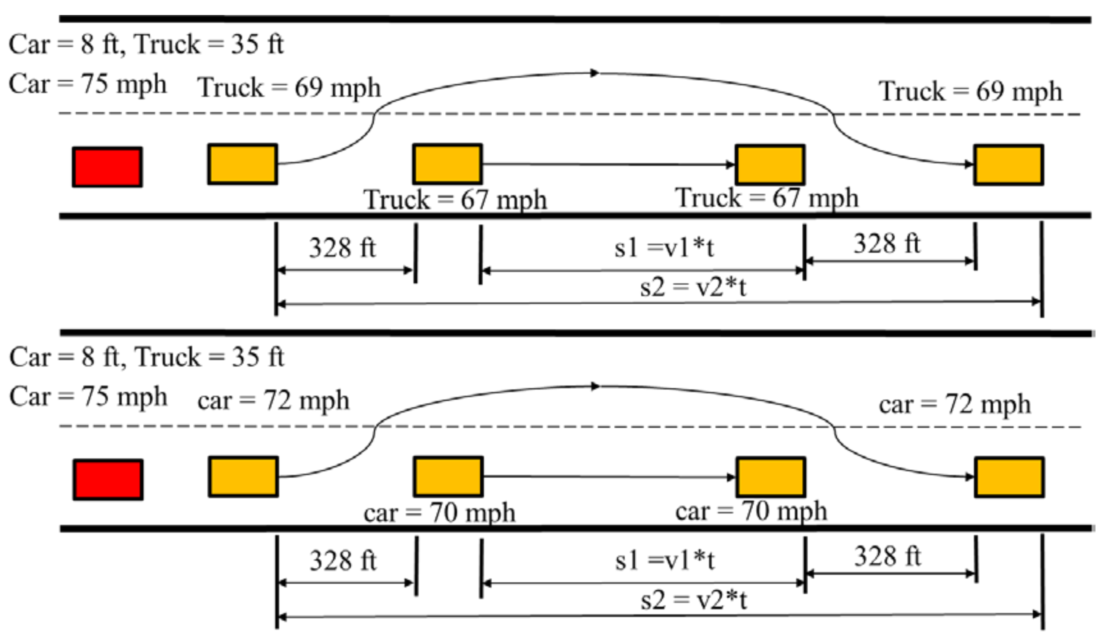


(h) tt-lagging headway

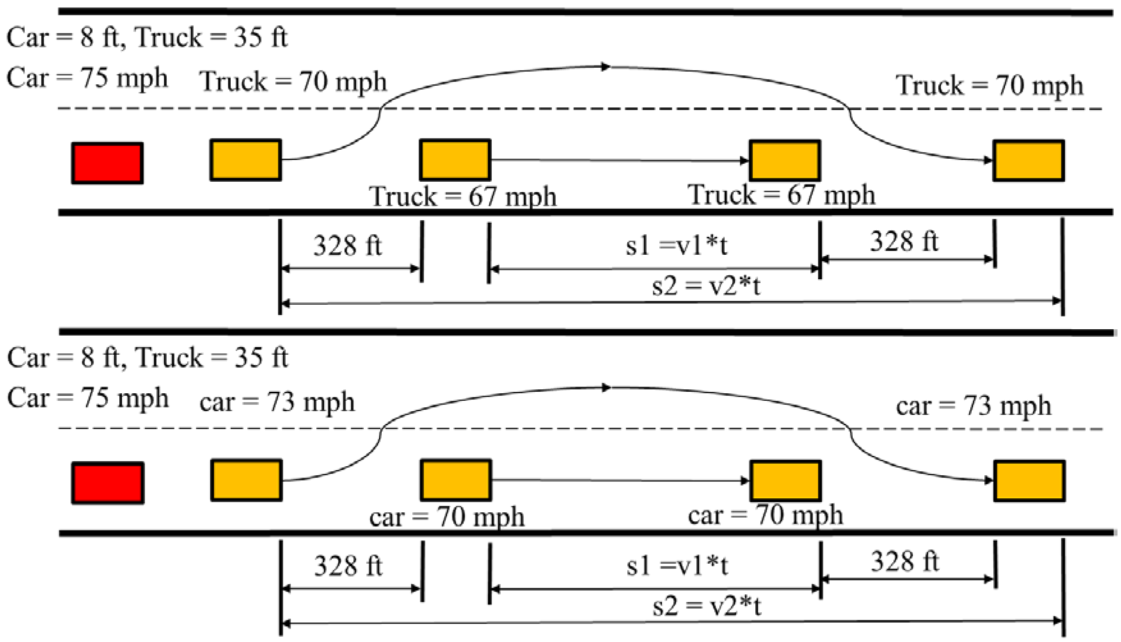
Appendix C: Conditions of theoretical analysis for platoon existence time and distance on two lanes with different platoon speed difference



(a) 1 mph

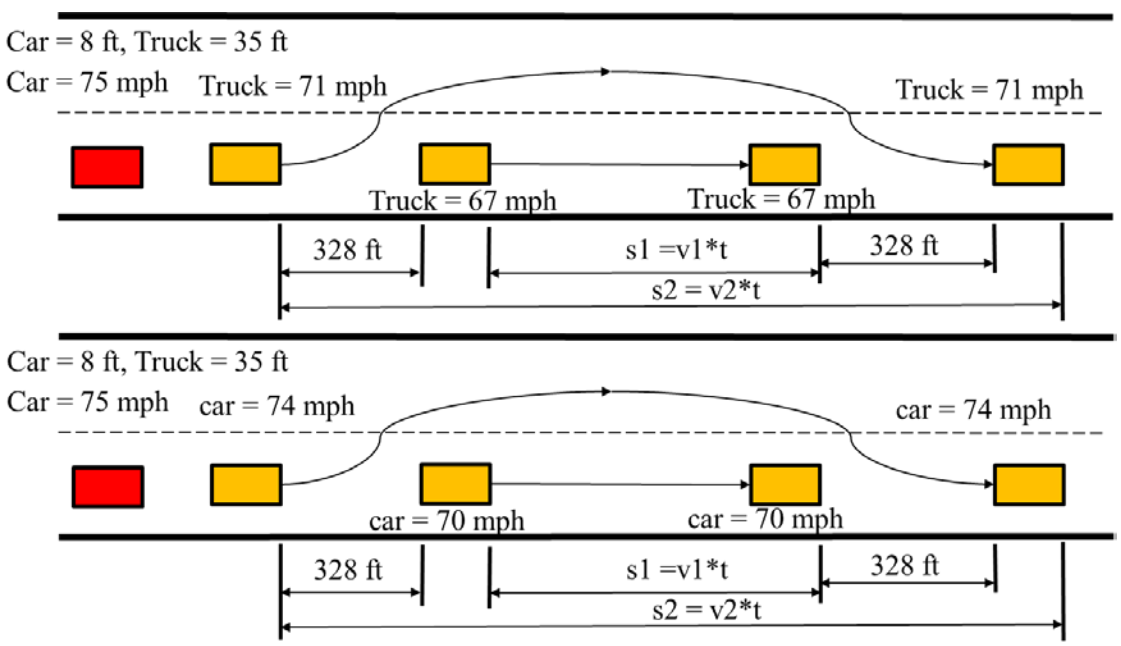


(b) 2 mph



Car = 8 ft, Truck = 35 ft
Car = 75 mph
Truck = 70 mph
Truck = 70 mph
Truck = 67 mph
Truck = 67 mph
328 ft
s1 =v1*t
328 ft
s2 = v2*t
Car = 8 ft, Truck = 35 ft
Car = 75 mph
car = 73 mph
car = 73 mph
car = 70 mph
car = 70 mph
328 ft
s1 =v1*t
328 ft
s2 = v2*t

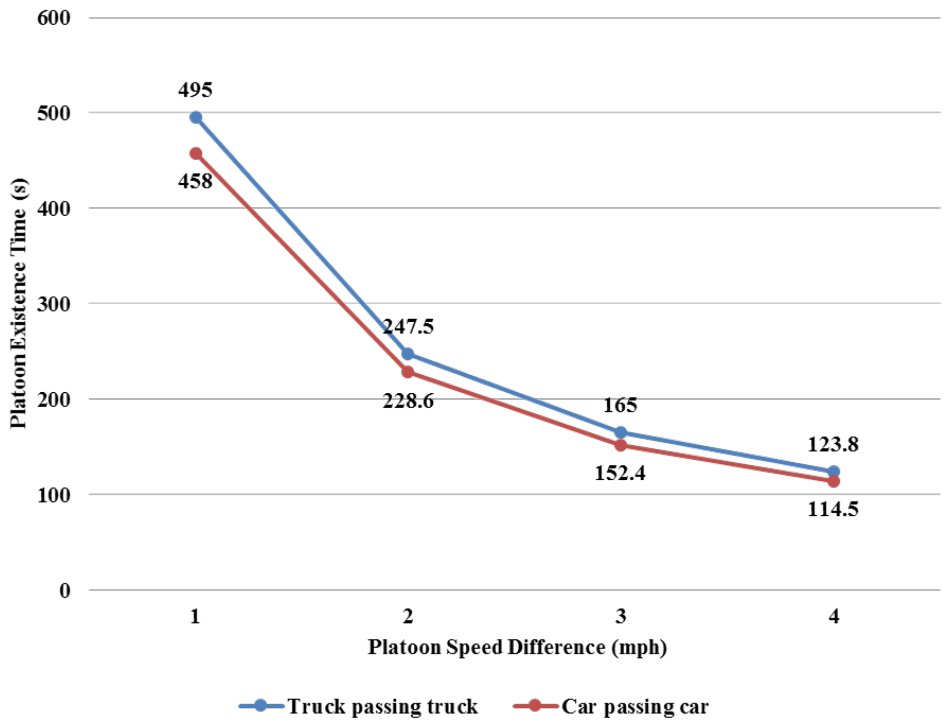
(c) 3 mph



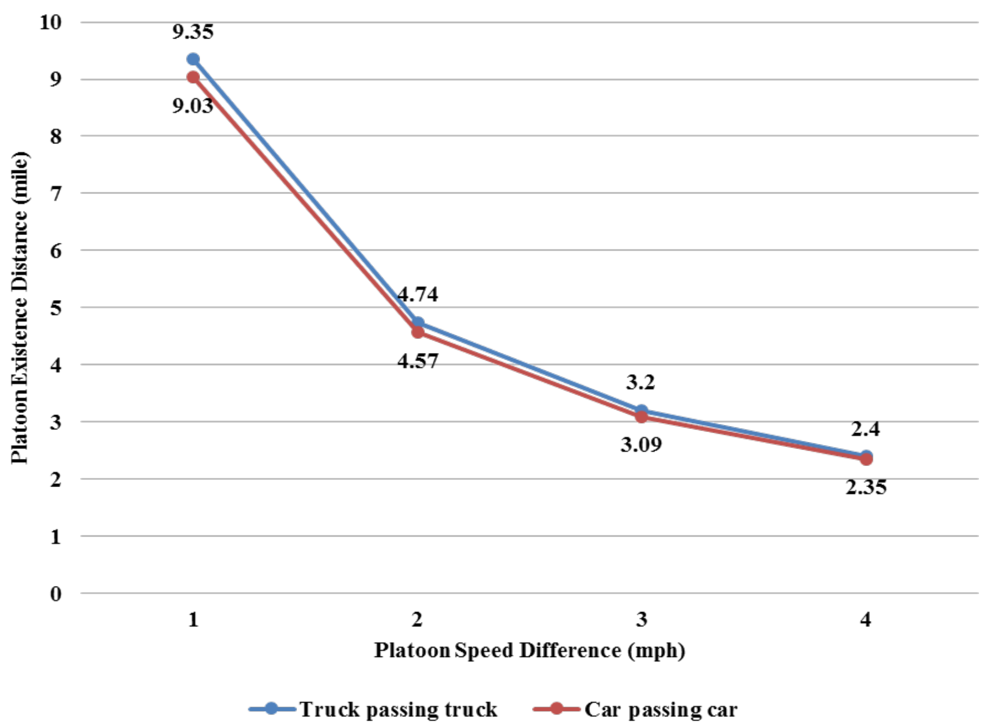
Car = 8 ft, Truck = 35 ft
Car = 75 mph
Truck = 71 mph
Truck = 71 mph
Truck = 67 mph
Truck = 67 mph
328 ft
s1 =v1*t
328 ft
s2 = v2*t
Car = 8 ft, Truck = 35 ft
Car = 75 mph
car = 74 mph
car = 74 mph
car = 70 mph
car = 70 mph
328 ft
s1 =v1*t
328 ft
s2 = v2*t

(d) 4 mph

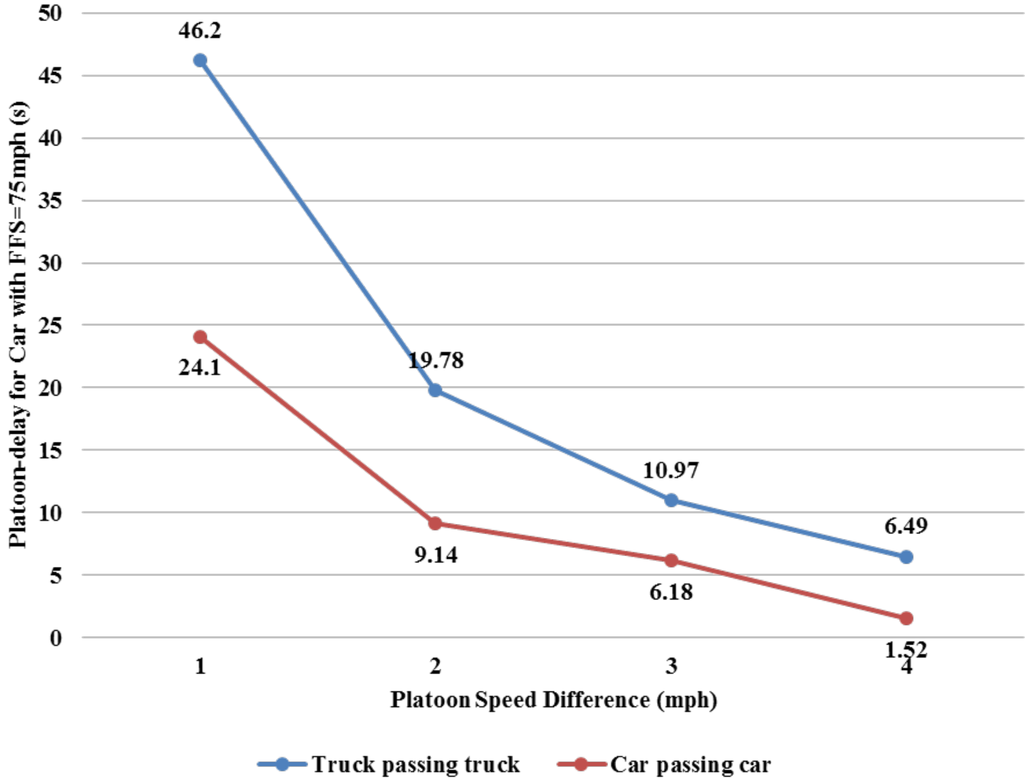
Appendix D: Results of theoretical analysis for effects of platoon speed difference



(a) Platoon existence time

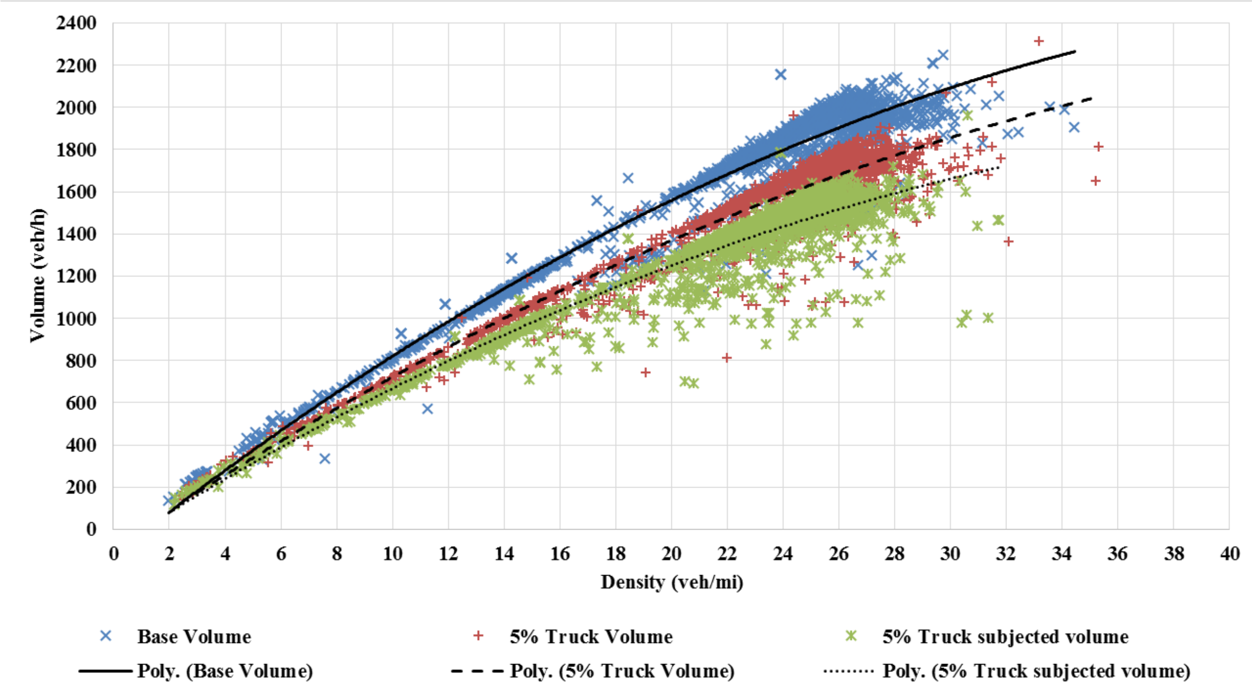


(b) Platoon existence distance

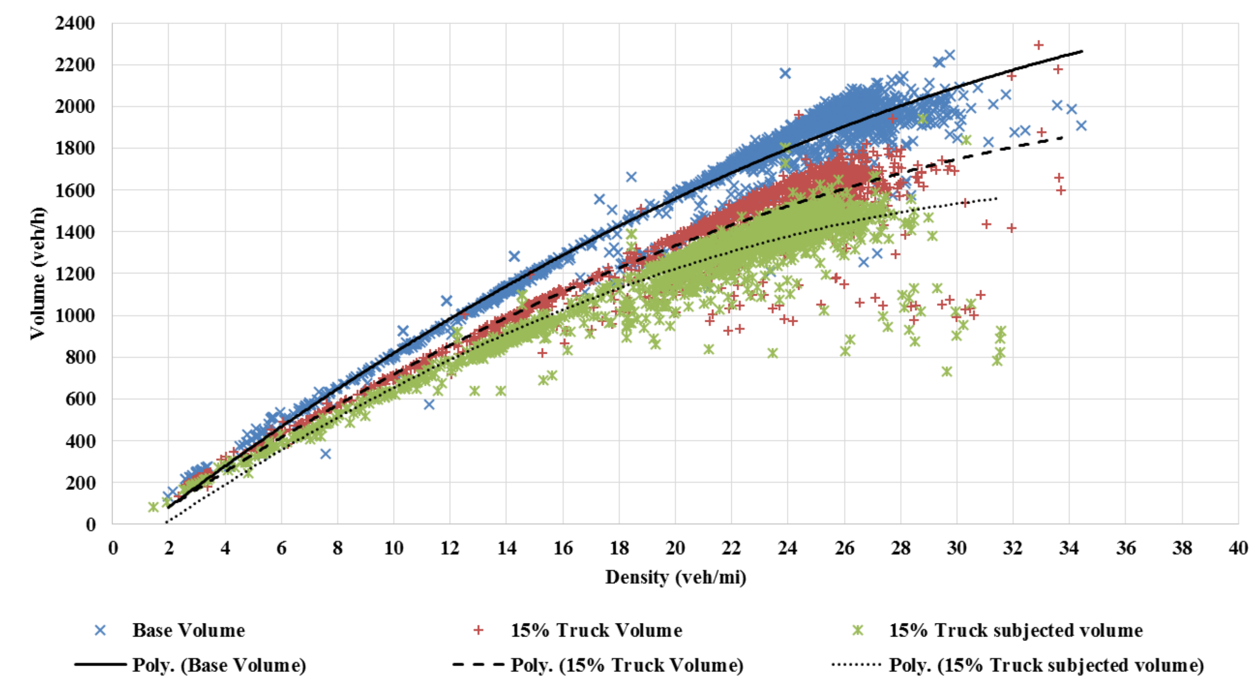


(c) Platoon delay for cars with FFS = 75 mph

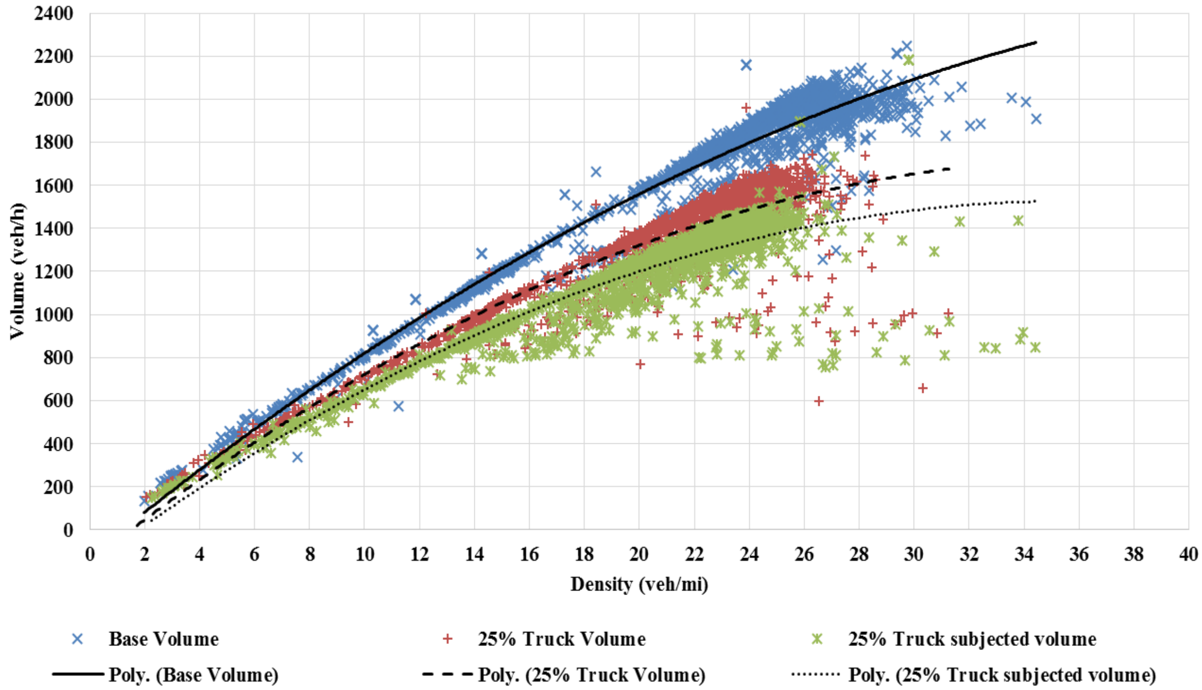
Appendix E: Volume-density curves for Nebraska and different speed distribution conditions



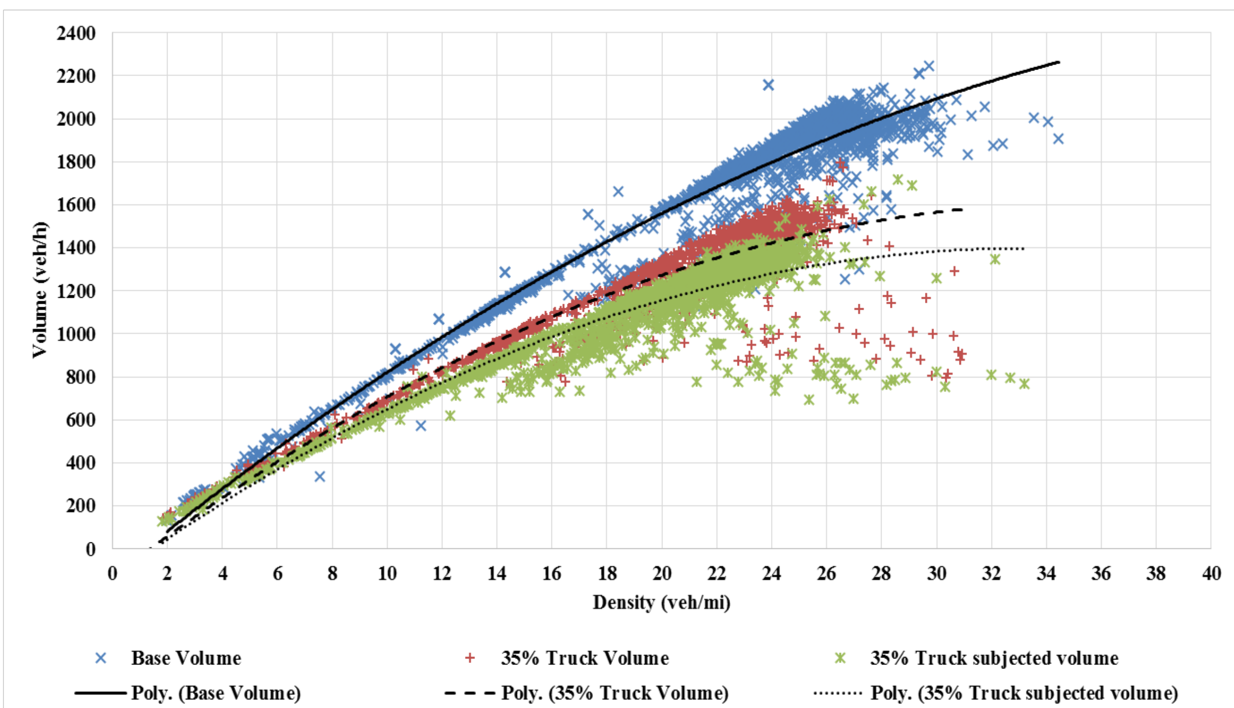
(a) 5% truck percentage



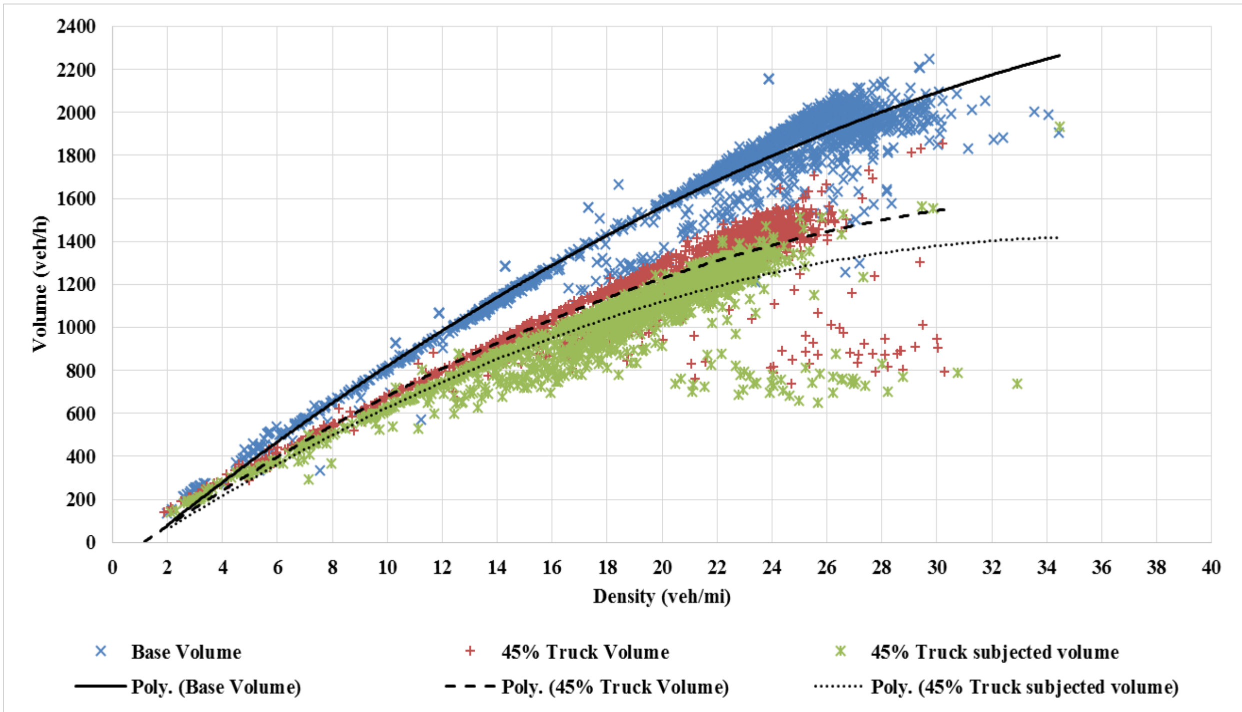
(b) 15% truck percentage



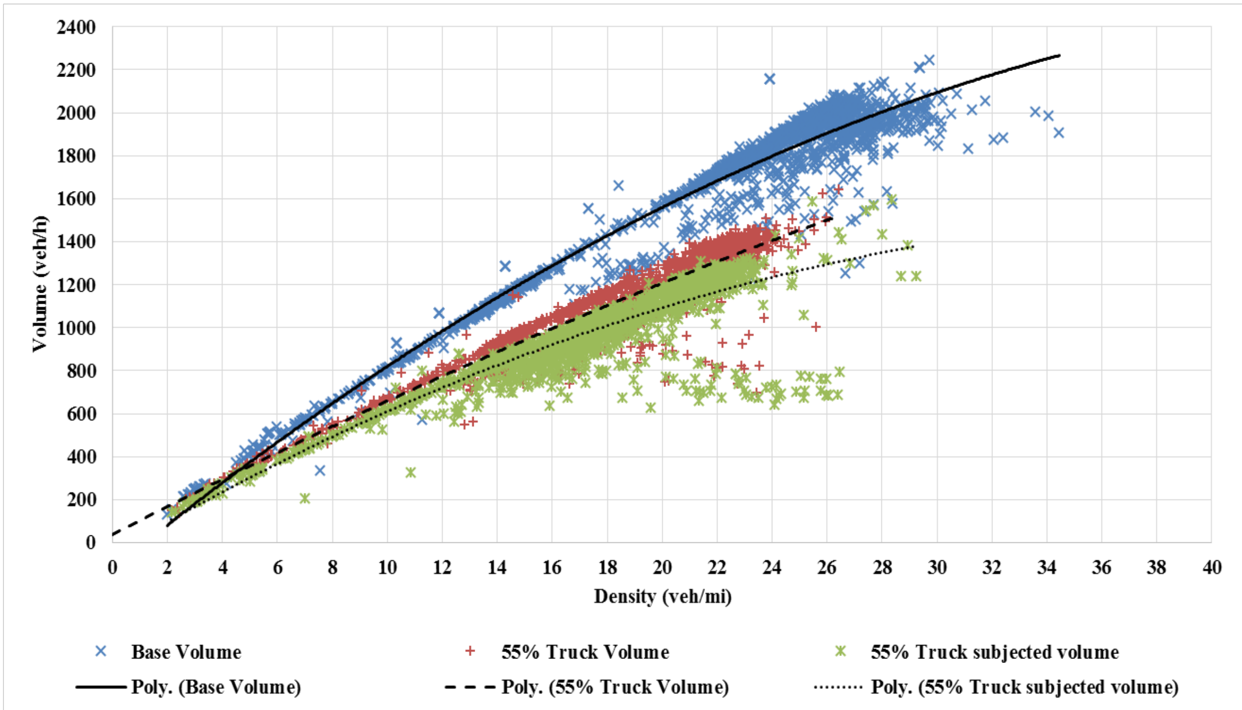
(c) 25% truck percentage



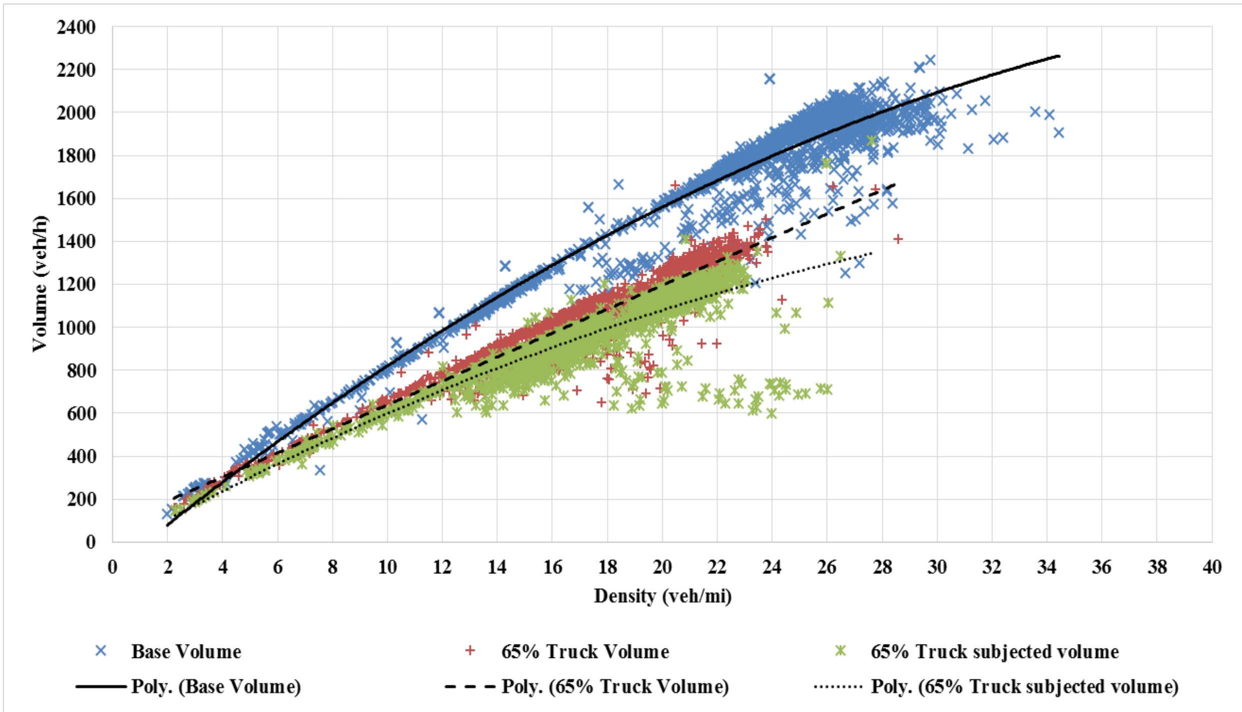
(d) 35% truck percentage



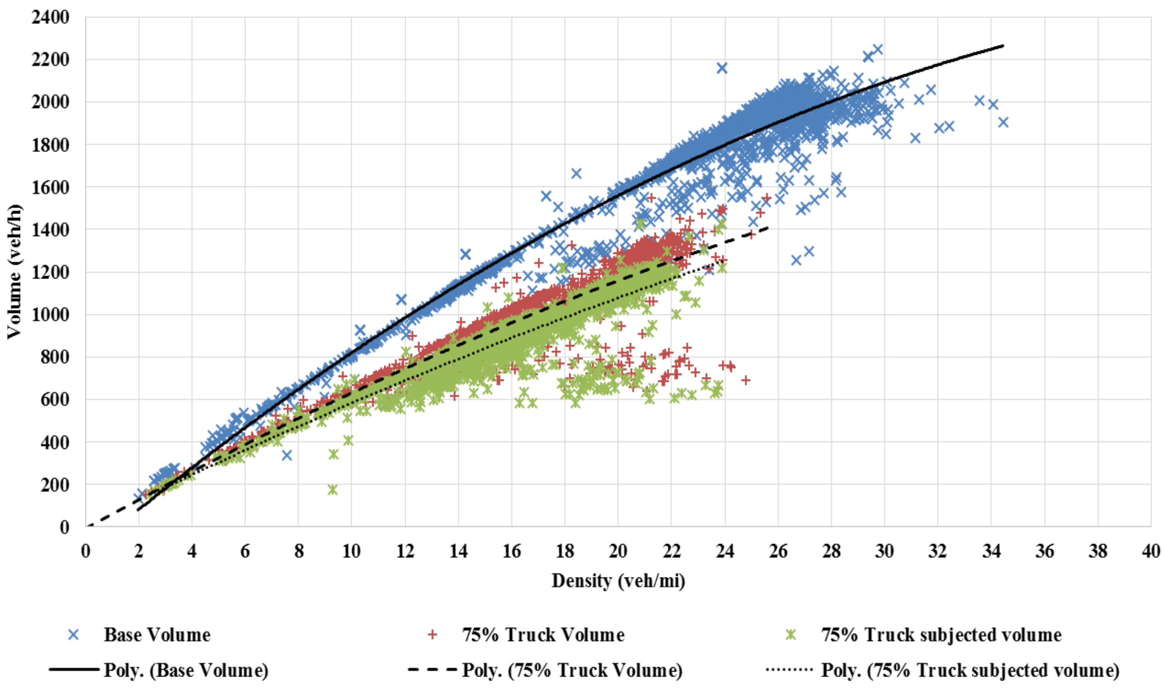
(e) 45% truck percentage



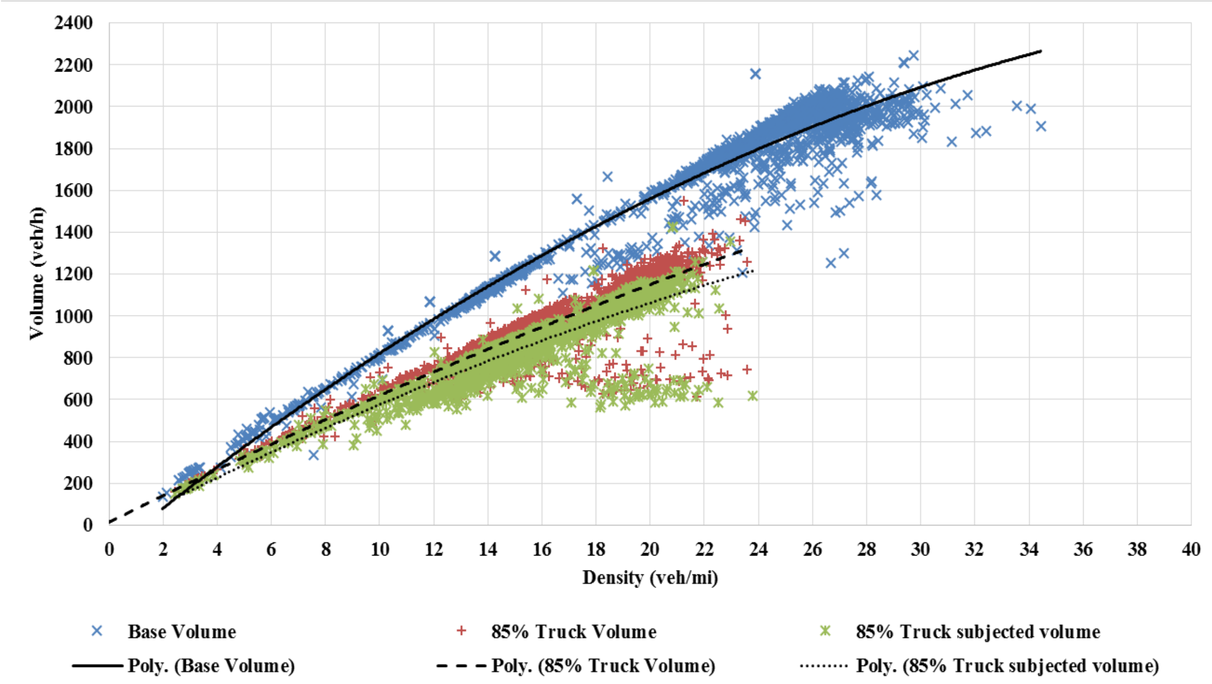
(f) 55% truck percentage



(g) 65% truck percentage



(h) 75% truck percentage



(i) 85% truck percentage