Passenger Car Equivalent Factors for Level Freeway Segments Operating under Moderate and Congested Conditions

Umama Ahmed
Marquette University

PASSENGER CAR EQUIVALENT FACTORS FOR LEVEL FREEWAY SEGMENTS OPERATING UNDER MODERATE AND CONGESTED CONDITIONS

by

Umama Ahmed

A Thesis Submitted to the faculty of the Graduate School,
Marquette University,
in Partial Fulfillment of the Requirements for
the Degree of Master of Science

Milwaukee, Wisconsin

August 2010

ABSTRACT
PASSENGER CAR EQUIVALENT FACTORS FOR LEVEL FREEWAY SEGMENTS OPERATING UNDER MODERATE AND CONGESTED CONDITIONS

Umama Ahmed

Marquette University, 2010

The significant impact Heavy Vehicles (HV) have on freeway operations has been identified since the first edition of the Highway Capacity Manual (HCM). The method of incorporating their impact in freeway capacity calculations has changed through the years. The HCM 2000 used Passenger Car Equivalent (PCE) values and percent of trucks/buses and Recreational Vehicles (RV) to account for HV effect on capacity. However PCE values in the most recent HCM edition rely on a limited field database and extensive simulation runs based on this information; they were calibrated on ‘steady-flow’ traffic operations. The objective of this effort was to indentify and quantify HV characteristics that have an impact of freeway throughput at various congestion levels on level, urban freeways using 1.2 million individual vehicle observations, with an emphasis on operations at LOS E and F. It was desired to use the products of this effort as recommended inputs for future simulation runs of congested freeway flow conditions. Passenger Car (PC) and HV headways were found to increase with HV presence in the traffic stream. A similar pattern was found for the PCE factor. The PCE value, under congested conditions and more than 9% HV presence, was found to be 1.76, which is higher than the HCM 2000-recommended value of 1.5 for level freeway sections. Also, passenger car was found to have the effect of more than 1 PC at congested condition with high HV presence.

ACKNOWLEDGEMENTS

Umama Ahmed

I would like to show my gratitude to my supervisor, Dr. Alexander G. Drakopoulos, for his encouragement and support, which enabled me to complete my thesis. I also appreciate the guidance given me by the members of my advisory committee: Professor David A. Kuemmel and Richard C. Coakley, P.E. My final acknowledgement is owed to my husband Mostafa Z. Uddin; and my parents: Faruque Ahmed and Nurjahan Begum, for their understanding, endless patience and encouragement when it was most required.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

CHAPTER 1. INTRODUCTION

1.1 Highway capacity, Heavy Vehicles and Passenger Car Equivalent (PCE) Values

Highway capacity is the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or a uniform section or lane of a roadway during a given time period under prevailing roadway and traffic conditions (1). It is expressed in passenger cars per hour per lane. The presence of large vehicles (Heavy Vehicles-HV) in the traffic stream results in a reduction in capacity. The reduction is due to the adverse effect of HV on traffic-stream performance. The following HV attributes that adversely impact capacity have been addressed in past research efforts:

1. HV are larger than Passenger Cars (PC), and thus take up more space in the traffic stream;
2. HV have operating capabilities (acceleration/deceleration) that are inferior to those of PC, thus requiring longer headways; and,
3. Drivers of nearby vehicles keep longer headways from HV.

To account for the adverse impact of HV present in a traffic stream in highway capacity analysis, traffic volumes containing a mix of vehicle types are typically converted into an equivalent flow of PC using Passenger Car Equivalents (PCEs). The procedure in the Highway Capacity Manual (HCM) allows freeway traffic volumes containing a mix of vehicle types and measured in vehicles per hour (vph) to be converted by the use of a HV factor, f_{HV}, into an equivalent flow rate of PC, measured in passenger cars per hour (pcph). The heavy vehicle adjustment factor has historically been based on separate PCE for trucks, buses, and Recreational Vehicles (RVs). The HCM 2000 (2) defines the heavy vehicle adjustment factor as:

$$f_{HV} = \frac{1}{1+P_t(E_t-1)+P_r(E_r-1)} \qquad 1.1$$

Where, E_t, E_r = PCE for trucks/buses and recreational vehicles (RVs) in the traffic stream, respectively;

P_t, P_r = Proportion of trucks/buses and RVs in the traffic stream, respectively;

f_{HV} = HV adjustment factor.

The HCM 2000 considered identical PCE values for both buses and trucks, assuming that there is no difference in their performance on freeways and multilane freeways.

Since the 1965 version of HCM, separate PCE values for HV were provided for level, rolling and mountainous terrain freeway segments. Level terrain has been defined as the "type of terrain that includes short grades of no more than 2 percent." In the HCM 2000, PCE for level freeway segments are considered to be 1.5 and 1.7 for Trucks and RVs respectively. These PCE values were calculated considering a steady-state flow condition. PCE values were independent of the level of service (LOS) prevailing on the freeway segment.

However, under steady-state flow conditions, the effect of HV on traffic flow can reasonably be expected to vary with prevailing traffic level due to the interaction between HV and smaller vehicles in the traffic stream. At low volumes, when drivers have relative freedom to choose their speeds, it is reasonable to expect that larger vehicles would have only a small effect on traffic flow. As congestion level increases, the HV effect can be expected to increase due to a greater interaction between vehicles in the traffic mix and reduced opportunities for drivers to pass slower-moving vehicles.

1.2 Research Objective

The significant impact HV have on freeway operations has been identified since the first edition of the HCM. The method of incorporating their impact in freeway capacity calculations has changed through the years. The HCM 2000 used PCE values and percent of trucks/buses and RV to account for HV effect on capacity. However PCE values in the most recent HCM edition rely on a limited field database and extensive simulation runs based on this information; they were calibrated on 'steady-flow' traffic operations.

The present effort investigates the effect of HV presence with a focus on congested and forced-flow conditions which are of major importance to practicing traffic engineers dealing with urban freeways facing recurrent congestion, freeway work zone- or traffic incident-caused congestion on a daily basis.

An extensive vehicle classification database that provided information about 1.2 million individual vehicles was used to analyze HV behavior on a level urban basic freeway section.

The objective of this effort was to indentify and quantify HV characteristics that have an impact on freeway throughput at various congestion levels, with an emphasis on operations at LOS E and F. It was desired to use the products of this effort as recommended inputs for future simulation runs specifically calibrated to replicate forced-flow conditions.

The extent of this effort was by necessity limited by the quantity of HV information collected under congested and severely congested conditions.

HV impacts were to primarily be assessed through investigations of the relations of HV headways with truck percentage in the traffic stream, gross vehicle weight and type of lagging-leading vehicle class combinations.

1.3 Thesis layout

Chapter 2 is a literature review of previous studies related to the effects of HV on freeway traffic flow and the development of PCE factors, including the description of the basis on which the HCM PCE factors were developed. The chapter contains a presentation of previous efforts on relationships between PCE and LOS; and HV effect on traffic flow. Chapter 3 states the methodology used to analyze the research hypotheses. Chapter 4 describes the study site and data collection procedure. A description of field data is also provided in this chapter. Chapter 5 is the data analysis chapter, which contains results on the research hypotheses. Chapter 6 presents the conclusions and recommendations drawn from the results of this research.

CHAPTER 2. LITERATURE REVIEW

This section includes the historical review of the Passenger Car Equivalent (PCE) concept for Heavy Vehicles (HV) on level freeway segments and describes different methods used to calculate PCE. Also the relationship of PCE with Level of Service (LOS) is discussed here. Previous research efforts on HV effect on traffic movement are also briefly stated in this chapter.

2.1 Historical review of development of PCE

The 1950 Highway Capacity Manual (HCM) introduced the estimate that, on two-lane highways on level terrain, trucks have the same effect as two Passenger Cars (PC). That HCM edition intimated that this estimate was based on the number of passenger cars passing trucks compared to the number of passenger cars passing passenger cars.

The 1965 HCM formally introduced both the Level of Service (LOS) concept and the term Passenger Car Equivalent (PCE). LOS was defined in terms of two parameters: operating speed and volume-to-capacity ratio. PCE for heavy vehicles was defined as “The number of passenger cars displaced in the traffic flow by a truck or a bus, under prevailing roadway and traffic conditions.” For two-lane highways, PCE was calculated considering different LOS. But for multilane highways operating under LOS B through LOS E, a constant PCE value of 2 was suggested for trucks. This was due to the fact that PCE values research in that area had been restricted principally to operation at or near LOS B; rationalized values for LOS E were developed, adapted from LOS B values by means of limited field data obtained during operation at capacity. The 1965 HCM suggested that further research was needed on PCE values for different LOS on multilane highways.

The 1985 HCM also related PCE with LOS for two-lane highways but for multilane level freeways a single value of 1.7 for trucks for all LOS was recommended.

The current 2000 HCM also uses a single PCE of 1.5 for level freeways, regardless of LOS. The currently suggested PCE value is based on the effect of HV dimensions and performance under steady-state traffic flow conditions.

2.2 Methods of Estimating PCE

Several approaches to estimate PCE values have been used. The most commonly applied approaches are as follows:

1. The constant volume-to-capacity ratio approach;
2. The equal-density approach; and,
3. The headway approach.

The constant volume-to-capacity ratio approach was developed based on the output of a multilane freeway simulation model developed at the Midwest Research Institute. PCE values were based on mixed traffic volumes that consumed the same proportion of roadway capacity (produced the same volume-to-capacity ratio) as PC-only volumes (3). The constant volume-to-capacity ratio approach was appropriate for calculating PCEs when LOS was a consideration for PCE calculation. But it is not applicable to the current procedure, which estimates PCE only under a steady-state condition (4).

The speed difference between the two traffic streams (PC-only and mixed traffic) when they operated at equal densities (measured in vehicle/mile) was used to determine PCE values. The practicality of PCE values based on this method was debated, since traffic streams operating at different speeds must have different degrees of freedom to maneuver. Thus it was suggested that the basis for equivalence of two traffic streams should not be equal density, but rather densities that feel the same to the driver in terms of proximity to other vehicles and freedom to maneuver (4).

The headway (time between successive vehicles in the traffic stream) approach uses actual measurements of the relative position maintained by drivers in the traffic stream under prevailing conditions to arrive at PCE values. The basic formula of PCE using the headway approach is as follows:

$$PCE = \frac{h_t}{h_c} \qquad \textbf{2.1}$$

Where, h_t = Average headway (in seconds) maintained by trucks following PC; and,
h_c = saturation flow headway of PC following PC.

This equation takes into account the effect of larger truck size and lower truck acceleration characteristics; truck drivers are expected to keep longer headways than PC following PC, thus PCE values are expected to be greater than 1 (5).

Two factors which affect PCE magnitude have traditionally been considered in PCE estimation: HV length and HV operating capabilities. Trucks, take up more space than PC; therefore headways for PC following trucks will be longer than those for PC following PC- the numerator of equation ***2.1*** will be larger than the denominator, increasing with truck length. In addition, inferior truck operating capabilities (lower acceleration rates and lower travel speeds) compared to PC require truck drivers to maintain longer headways from leading vehicles than PC drivers maintain, contributing to a large numerator in equation ***2.1.***

Ideally the numerator and denominator of equation ***2.1*** are based on actual field observations. Field measurements include the effects of both above-mentioned factors and maybe other factors as well that are yet to be identified.

Krammes et al. (4) analyzed a mixed traffic stream and developed an equation considering headway differences between trucks and other vehicles, as shown below:

$$PCE = \frac{(I-p)(h_{pt} + h_{tp} - h_{pp}) + p h_{tt}}{h_{pp}} \qquad \textbf{2.2}$$

Where, p = percentage of trucks at a mixed traffic stream;
h_{pt} = Mean headway time in seconds for trucks following PC;
h_{tp} = Mean headway time in seconds for PC following trucks;
h_{pp} = Mean headway time in seconds for PC following PC;
h_{tt} = Mean headway time in seconds for trucks following trucks.

Krammes et al. (4) recommended equation ***2.2*** as the final formulation for use in highway capacity analysis instead of equation ***2.1*** because it accounts separately (and thus more accurately) for the impact of trucks leading or following PC or other trucks.

2.3 Relation with LOS

Krammes et al (4) analyzed data collected from six-lane, basic level freeway segments on the Kingery Expressway in Chicago and on the La Porte Freeway in Houston. Lagging time headways were measured for four combinations of pairs of PC and trucks in a mixed traffic stream. The four combinations were: PC following a PC, PC following a truck, truck following another truck, and a truck following a PC. The mean lagging headway time was estimated using an analysis of covariance model. The model was calibrated with a range of flow rates from approximately 400 to 1,300 vehicles per hour per lane. To avoid extrapolation beyond the limits of the data, predicted values were estimated only for flow rates and speeds that approximated the upper traffic density limits of LOS A, B, and C. PCE values for trucks were computed using the mean headway, proportion of trucks in each lane and LOS. The results indicated that PCE values (based on equation ***2.2***) increased as LOS decreased from A to C. However, they suggested more work on their suggested PCE calculation method and did not recommend their results as conclusive findings. Table 2.1 shows the estimated PCE values for each LOS and each lane found from the study. It also shows the overall PCE value for all lanes combined for each LOS. This overall value is a weighted average of the value for each lane, weighted according to the distributions of trucks by lane at each LOS.

Webster et al. (6) did a study to find the effect of traffic flow rate on PCE for basic level freeway sections using the FRESIM simulation model. PCEs were calculated for five truck types having differing weight-to-power ratios and overall lengths. The five truck types examined were: semi-trailer with five axles, single unit truck with two axles, semi-trailer with four axles, double trailer truck with five axles, and triple trailer truck. Flow rates tested were at 500, 1000, 1500 and 2000 vphpl. Table 2.2 shows the resulting PCE values for the five subject truck types examined. The study results indicated that, PCE is sensitive to traffic flow rate at level grades, and that, in general, PCE increases with traffic flow rate.

TABLE 2.1 Estimates of PCE values for Trucks on Level Freeway Segments from Krammes et al. Study (4).

Lane	Vehicle of Interest Type	Leading Vehicle Type	Truck PCE		
			Level of Service		
			A	B	C
Right	PC	PC	3.89	2.62	1.99
		Truck	4.10	2.76	2.10
	Truck	PC	5.12	4.35	3.90
		Truck	3.92	3.33	2.99
Center	PC	PC	3.80	2.34	1.71
		Truck	3.67	2.26	1.65
	Truck	PC	3.72	2.73	2.20
		Truck	3.10	2.27	1.83
Median	PC	PC	2.54	1.73	1.31
		Truck	3.02	2.05	1.55
	Truck	PC	4.23	3.37	3.13
		Truck	1.37	1.09	1.01

TABLE 2.2 Effect of Traffic Flow Rate on PCE at Level Grades found from Webster et al. Study (6).

Traffic flow rate (vphpl)	PCE				
	Semi-trailer with five axles	Single unit truck with two axles	Semi-trailer with four axles	Double trailer truck with five axles	Triple trailer truck
500	1.02	1.03	1.09	1.02	1.02
1000	1.05	1.05	1.04	1.06	1.07
1500	1.14	1.07	1.06	1.12	1.16
2000	1.42	1.04	1.15	1.42	1.62

Al-Kaisy et al. (7) hypothesized that the effect of HV on freeway traffic is greater when the facility is operating at oversaturated conditions than when it is operating at undersaturated (below-capacity) conditions. That hypothesis was based on the fact that during congestion or stop-and-go conditions, the acceleration and deceleration cycles, are expected to impose an extra limitation on the performance of HV, and that may affect the PCE value. The data were collected from a level freeway segment with 3 lanes in one direction during the morning peak hours (7:30 to 9:30 am). Congestion was due to heavy commuter traffic during that time period. A total of 27 data sets, each containing several 5-min vehicle observations, comprising more than 38 hours of capacity observations were collected using video recording. Table 2.3 shows the summary of PCE factors and the mean capacity that resulted from individual optimization runs for that site.

The PCE factors ranged from 1.70 to 5.48 (see Table 2.3). The PCE value greater than 4.00 was found in three data sets where the weather became rainy midway of the count. The authors suggested a few reasons why these days should not be considered as valid. Typically at that site, PC counts used to decrease and HV counts used to increase as time progressed at the morning. In those three days, the decrease in PC counts should have been attributed to two factors; the increase in HV counts and the rainy weather. Optimization simply attributed all the reduction in PC counts to the increase in HV counts and therefore the PCE factors were overestimated. Neglecting those data sets and considering the remaining ones, a mean PCE value of 2.36 was found. This value is considerably higher than the corresponding PCE factor of 1.5 recommended by the HCM 2000 which was calculated for traffic under steady-state conditions. Therefore, the research hypothesis that the PCE value for HV during oversaturated conditions is higher than the PCE value during free flow condition was validated. In light of this finding, the authors recommended the use of a more realistic PCE factor for HV for calculating queue discharge flow capacity (7).

TABLE 2.3 Summary of PCE and Capacity values found for Al-Kaisy et al. Study (7).

Date	Time	No. of Observations	PCE	Capacity (pcphpl)	Weather	Maintenance
May 16, 2000	AM	17	2.52	2283	Dry	No
May 17, 2000	AM	19	1.77	2157	Dry	No
May 18, 2000	AM	16	2.18	1986	Dry then rainy	No
May 19, 2000	AM	15	4.26	2379	Dry then rainy	No
May 23, 2000	AM	18	4.09	2343	Dry	No
May 24, 2000	AM	15	2.18	2223	Dry	No
May 25, 2000	AM	18	2.05	2154	Dry	No
May 29, 2000	AM	16	2.58	2210	Dry	No
May 30, 2000	AM	18	2.19	2187	Dry	Yes
June 1, 2000	AM	21	2.84	2256	Dry	Yes
June 2, 2000	AM	22	1.78	2102	Dry	Yes
June 5, 2000	AM	15	2.32	2051	Dry	Yes
June 6, 2000	AM	17	3.21	2283	Dry	Yes
June 7, 2000	AM	17	2.1	2224	Dry	Yes
June 12, 2000	AM	17	2.53	2291	Dry	No
June 13, 2000	AM	21	2.55	1843	Rainy	No
June 14, 2000	AM	20	2.19	1918	Rainy	No
June 16, 2000	AM	13	1.70	2169	Dry	No
June 19, 2000	AM	16	2.17	2230	Dry	No
June 20, 2000	AM	14	2.75	2245	Dry	No
June 21, 2000	AM	22	2.43	2014	Rainy	No
June 22, 2000	AM	16	2.42	2242	Dry	No
June 23, 2000	AM	13	2.35	2297	Dry	No
June 26, 2000	AM	15	3.35	2321	Dry	No
June 27, 2000	AM	17	2.24	2225	Dry	No
June 28, 2000	AM	17	2.35	2257	Dry	No
June 29, 2000	AM	16	5.48	2627	Dry then rainy	No

The Institute for Research study (8) produced a set of PCE values for a broad range of vehicle types on urban level freeways under five hourly volume levels (0-599 vphpl, 600-999 vphpl, 1000-1499 vphpl, 1500-1799 vphpl and 1800-2000+ vphpl). For Single-unit trucks and buses, PCE values ranged from 1.1 at 0-599 vphpl to 1.6 at 1800-2000+ vphpl volume level. For Tractor Trailers PCE values found to be 1.1 at 0-599 vphpl to 2.0 at 1800-2000+ vphpl. PCE was calculated based on 5 minute flow. The results indicated that PCE values varied based on volume levels, increasing with increasing volume. This finding agreed with the findings of Webster et al. (6). However Roess et al. (3) concluded that the idea of varying PCE for varying volume level would be a vexing one. Their logic behind the conclusion was that, the adoption of PCE values varying with volume would present serious problems in capacity analysis procedures, greatly complicating computations. Because the design benefits of smaller PCEs at low volumes would be minimal, they recommended that constant PCEs with volume should be used for vehicle types on level terrain; however, they did not provide a specific suggestion about which PCE value at which volume should be used.

2.4 Effect of heavy vehicles

To examine the effect of heavy vehicles on the movement of a mixed traffic stream, Sarvi (9) observed the behavior of 240 vehicles in which 120 were HV-following-PC, and 120 were PC-following-PC and PC-following-HV under congested traffic conditions. Each vehicle-following case was analyzed in microscopic detail over a length of 700 meters over which the speed and position of each vehicle were identified. Results indicated that there was a significant difference in the vehicle-following behavior of HV compared to that of PC. HV drivers were found to keep longer headways and spacings when following other vehicles. PC drivers were found to travel further behind HV (in terms of headway and spacing) than when following other PC. Also, PC-following-HV headways were found to be longer than HV-following-PC headways. Based on these results, the author concluded that, there was a significant difference in the vehicle-following behavior of HV; also the presence of a HV in a leading position in the traffic stream had a significant negative effect on the headways kept by trailing vehicles (resulted in longer headways by trailing drivers).

Y. Tanaboriboon et al. (10) conducted research to evaluate the effect of vehicle size on highway capacity in Thailand. The headway for 5 min and 15 min flow was collected when the freeway section was at or near its capacity (LOS E). Headway data were obtained from a mixed traffic stream as well as a traffic stream containing only small vehicles due to imposed HV restrictions. The researchers observed that the proportion of HV in a traffic lane affected the average headways of all types of vehicles. Comparisons of headways kept between pairs of vehicles for different vehicle pair types indicated the following:

i. Headways involving small vehicles with medium-sized vehicles, taken as a group, were significantly shorter than those involving HV with the two other sizes (small and medium) and with each other.

ii. Headways involving HV following medium-sized or small vehicles were not significantly different from each other.

iii. The overall effect of HV on capacity during the peak flow hour under prevailing traffic conditions was capacity reduction on the order of 15%.

The authors concluded that their findings impact should be taken into consideration for PCE calculations. Table 2.4 shows the headway data collected for different leading-following vehicle combinations.

Similar results were obtained in a study by Krammes et al. (4). Headway data were obtained from a field dataset with flow rates ranging from 400 to 1,300 vehicles per hour per lane which approximated conditions of LOS A, B and C. It was found that, 95 percent of the time, PC maintained slightly higher headway and spacing when traveling behind HV than PC. Also, it was observed from the headway data that, vehicle headways decreased with increasing congestion level (see Table 2.5).

TABLE 2.4 Mean Headway for different Leading-Lagging Vehicle Combination found at Tanaboriboon et al. Study (10).

Mean Headway (s)	Leading-Lagging vehicle combination
3.23	Medium-Large
3.20	Small-Large
2.92	Large-Large
2.67	Large-Medium
2.54	Large-Small
2.14	Small-Medium
2.06	Medium-Medium
1.97	Medium-Small
1.95	Small-Small

TABLE 2.5 Mean Headway for different Leading-Lagging Vehicle Combination found at Krammes et al. Study (4).

Lane	Vehicle of Interest Type	Leading Vehicle Type	Headway (s)		
			Level of Service		
			A	B	C
Right	PC	PC	3.89	2.62	1.99
		Truck	4.10	2.76	2.10
	Truck	PC	5.12	4.35	3.90
		Truck	3.92	3.33	2.99
Center	PC	PC	3.80	2.34	1.71
		Truck	3.67	2.26	1.65
	Truck	PC	3.72	2.73	2.20
		Truck	3.10	2.27	1.83
Median	PC	PC	2.54	1.73	1.31
		Truck	3.02	2.05	1.55
	Truck	PC	4.23	3.37	3.13
		Truck	1.37	1.09	1.01

There were several differences of the studies by Tanaboriboon et al. (10) and Krammes et al. (4):

I. Data for two studies were collected from two different continents; one from Asia and another from North America.

II. Data for the study by Tanaboriboon et al. (10) were collected when the freeway section was at capacity (LOS E), whereas data for the study by Krammes et al. (4) were collected during free-flow conditions (LOS A to C).

Despite these differences, the Tanaboriboon et al. and Krammes et al. studies provided some important insights of vehicle headway behavior with changing congestion level:

I. The headway maintained by trailing vehicles is dependent on congestion level.

II. Headway decreases with increasing congestion level (headway decreases with decreasing LOS).

III. Drivers of all vehicles keep the longest headways under free-flow conditions and the shortest headways at forced-flow conditions.

CHAPTER 3. METHODOLOGY

3.1 Passenger Car Equivalent Factor Calculation Method

Among the methods that have been used to calculate the Passenger Car Equivalent factor (PCE), the headway ratio method based on the following equation was used in the present effort:

$$PCE = \frac{HV\ headway}{PC\ headway} \quad \textbf{3.1}$$

The numerator of equation ***3.1*** is the Heavy Vehicle (HV) headway measured under a given set of traffic flow conditions; the denominator is the measured Passenger Car (PC) headway at capacity, measured in a PC-only traffic stream. Thus the HV effect on the traffic stream under a given set of traffic flow conditions is represented by the additional time consumed by the HV present in the traffic stream.

3.2 Regression Analysis

A regression analysis was performed using the Statistical Package for the Social Sciences (SPSS) software in order to evaluate the fit of various models (equations) to the relationship of headway (dependent variable) with average speed (fixed factor). The best-fitting equation among a set of eleven tested models (linear, quadratic, cubic, logarithmic, inverse, power, compound, S, logistic, growth and exponential) was chosen for presentation in this thesis.

3.3 Analysis of Variance (ANOVA)

Analysis of Variance using the SPSS software package was used extensively in order to establish general descriptive headway statistics as well as the 95% Confidence Intervals (95% CI) for mean headway values. Detailed explanations on the use of ANOVA results are provided in section 5.5.1.

3.4 Headway Measurement

The difference between the time at which the front axle of the leading vehicle and the front axle of the trailing vehicle crossed the detector loop was considered as the trailing vehicle's headway for this research. Headway was measured in seconds. Headways calculated in this manner for individual vehicles were cross-checked using the relationship between hourly volume and headway.

3.5 Vehicle Classification

Vehicles in the field data set for this thesis had been classified according to the Federal Highway Administration (FHWA) classification. FHWA classifies vehicles into 13 classes; vehicles within classes greater than 3 would be defined as heavy vehicles for Highway Capacity Manual purposes. Figure 3.1 shows the FHWA vehicle classification. Table 3.1 presents the average gross vehicle weight of each vehicle class present in the field data.

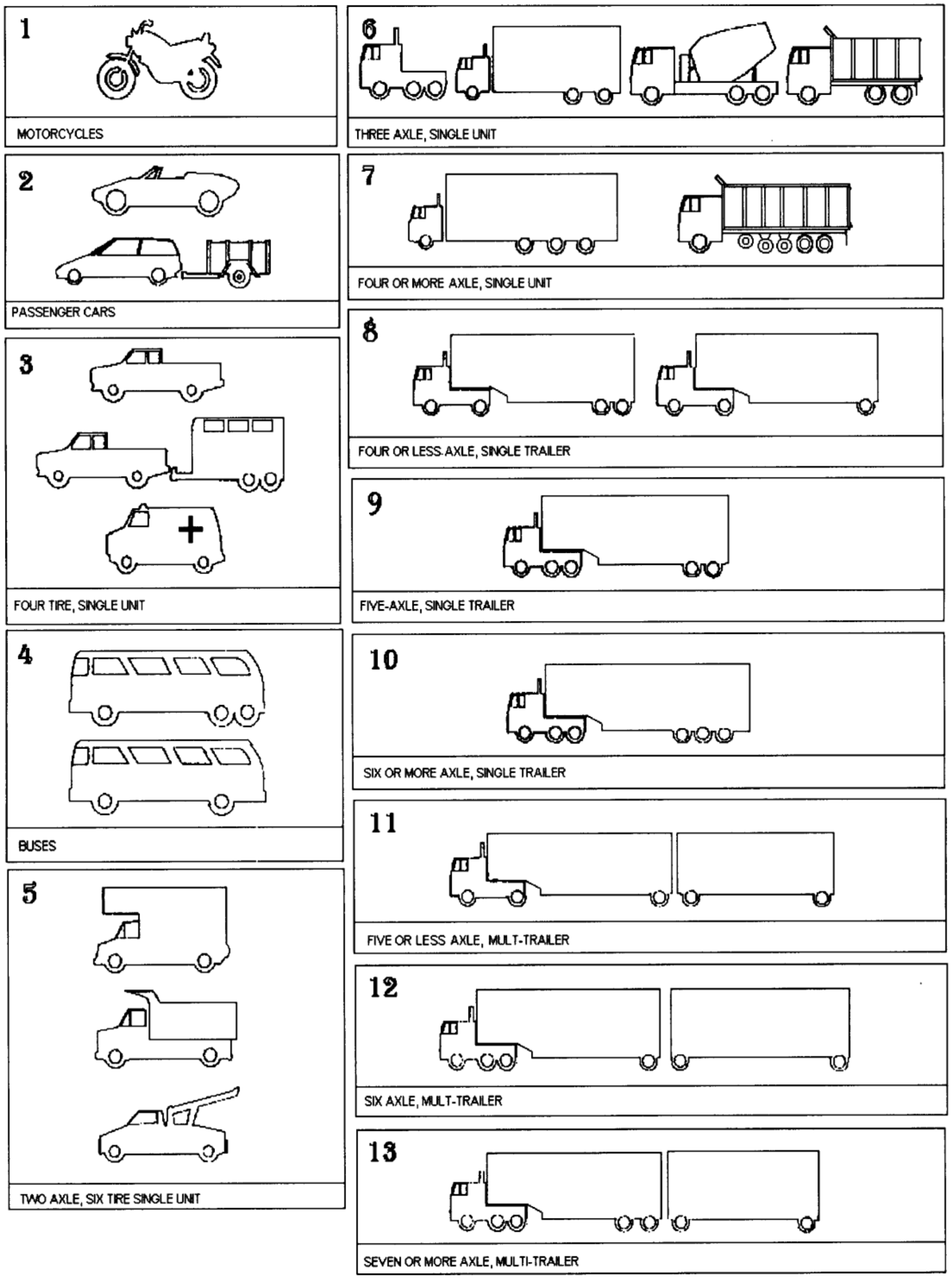

FIGURE 3.1. FHWA Classification of vehicles. (Source: FHWA Traffic Monitoring Guide)

TABLE 3.1 Average gross vehicle weight for all vehicles present in the field data set.

Vehicle class	Average Gross Vehicle Weight (kips)
2	3.3
3	5.5
4	21.4
5	12.3
6	29.7
7	47.2
8	39.6
9	59.2
10	59.0
11	64.2
12	59.1
13	62.8

CHAPTER 4. AVAILABLE DATA

4.1 Data Collection Site

The present analysis is based on field data collected in the southbound direction of a six-lane section of Interstate 43 located just North of downtown Milwaukee, Wisconsin (population 630,000). The data collection site (see Figure 4.1) was preceded by an 8,000 ft straight and level section with 12 ft lanes and 12 ft shoulders on both sides. The section speed limit was 55 mph; it dropped to 50 mph 1,000 ft upstream of the detector location. On-and off-ramps were present at regular intervals of approximately 0.75 mile. Data were collected through detectors placed immediately South of the Wright Street overpass (see Figure 4.1) in each of the three southbound lanes.

4.2 Data Collection System Description

The installed data collection system consisted of a controller cabinet containing the Central Processing Unit (CPU) (Figure 4.2), connected to pavement-embedded detector arrangements (Figure 4.3). Separate detector sets were placed within each lane of travel. Each set consisted of two loop detectors with a piezo-electric vehicle weight sensor between them. Detector signals were sent to the CPU for processing and storage.

4.3 Data Description

Field data were collected for a total of twenty-one days between August 29, 2002 and September 29, 2002 (see Table 4.1). The raw data consisted of the date and time at which the vehicle crossed the detectors, the FHWA vehicle class, vehicle length in feet, speed in mph, number of axles, individual axle weight, vehicle wheelbase(s) and the lane in which the vehicle was traveling.

A total of 1,201,053 vehicles were counted during the study period; 415,243 vehicles traveled in the median lane, 438,604 vehicles in the middle lane and 347,206 in the shoulder lane (see Table 4.1). Data were analyzed using the Statistical Package for Social Sciences (SPSS) software.

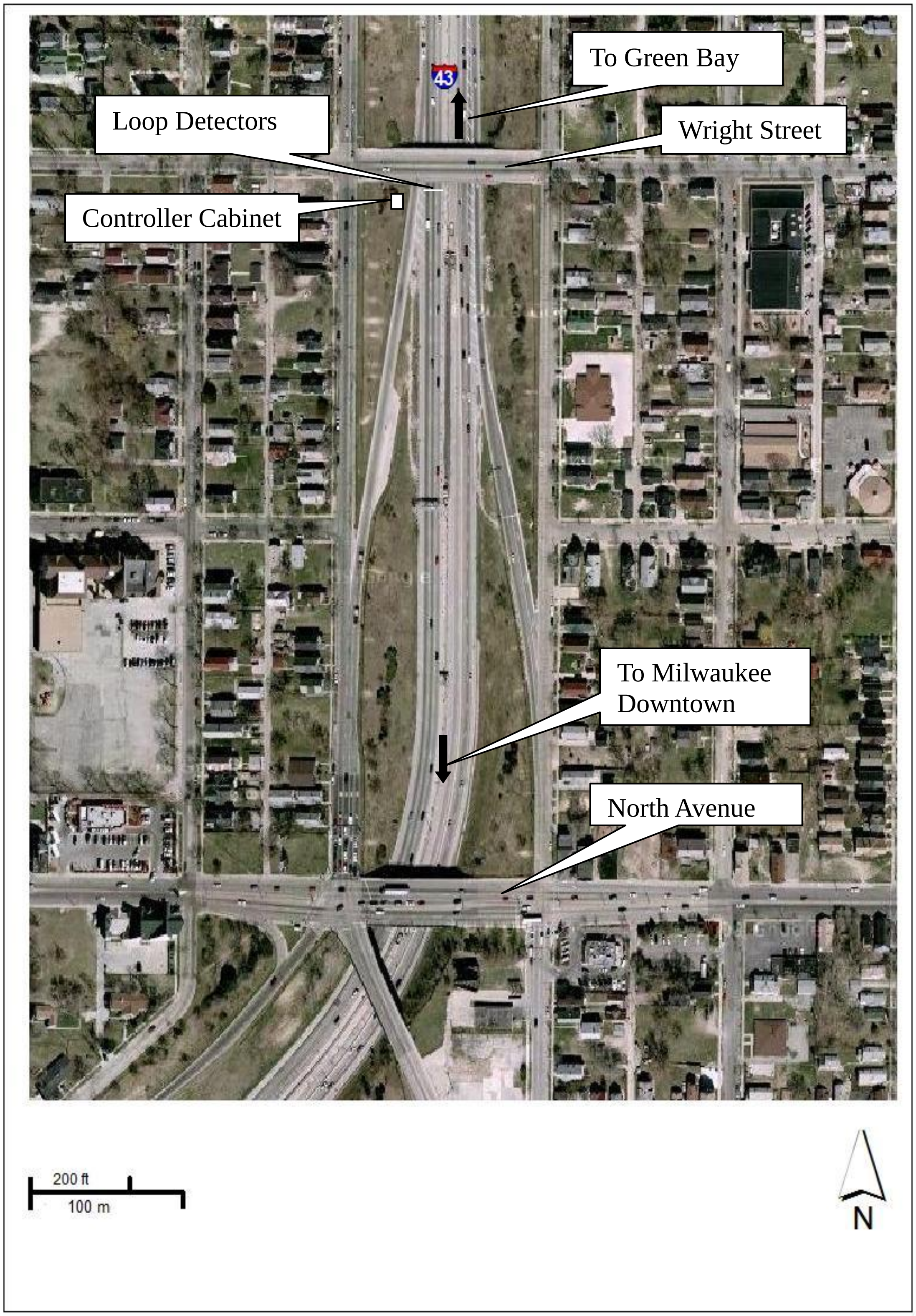

FIGURE 4.1. Data Collection Site.

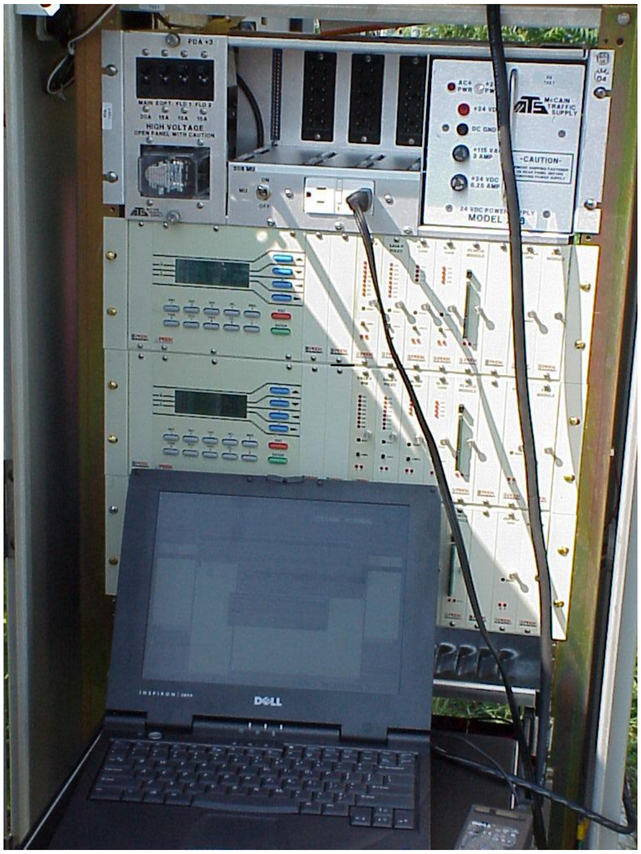

FIGURE 4.2. Central Processing Unit in the controller cabinet.

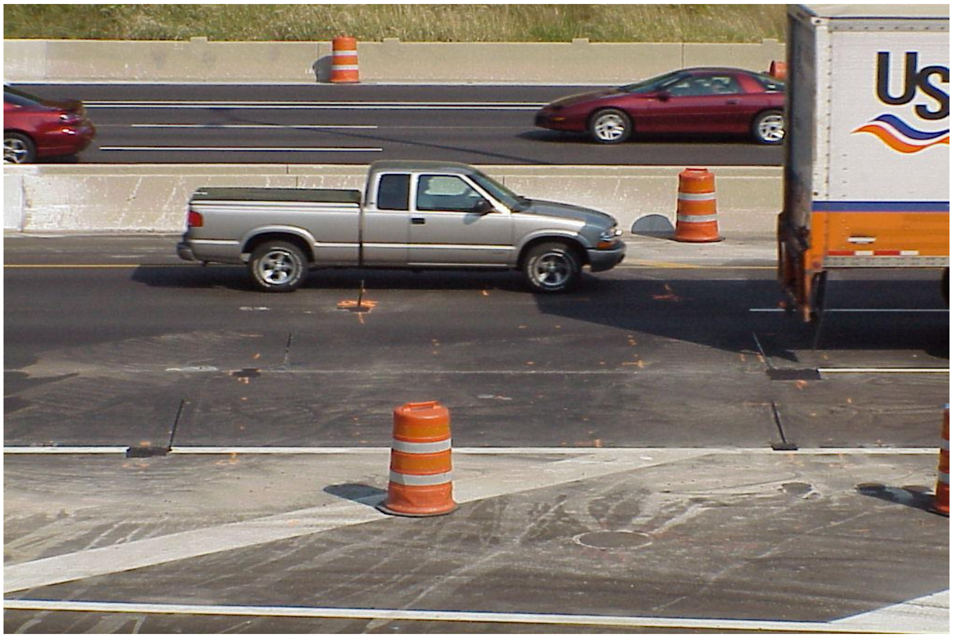

FIGURE 4.3. Pavement-embedded detectors, saw cuts and pull box visible.

TABLE 4.1 Number of vehicle observations by date and by lane.

Date	Number of observations			
	Lane			
	Median	Middle	Shoulder	Total
08/29/2002	8604	8293	7251	24148
08/30/2002	22796	23933	18758	65487
08/31/2002	15622	22467	16023	54112
09/01/2002	13030	19512	13953	46495
09/02/2002	15272	19460	13902	48634
09/03/2002	23388	23564	13501	60453
09/04/2002	23663	23729	18532	65924
09/05/2002	23668	21762	18308	63738
09/06/2002	23625	23079	19872	66576
09/08/2002	14321	19879	14474	48674
09/07/2002	16474	22194	16706	55374
09/11/2002	25581	20727	17399	63707
09/12/2002	25955	21443	17188	64586
09/13/2002	24247	10348	19369	53964
09/15/2002	12797	19036	14107	45940
09/22/2002	14368	19890	15200	49458
09/23/2002	21588	23608	19737	64933
09/25/2002	24549	24798	19487	68834
09/26/2002	24990	25170	19053	69213
09/27/2002	25657	25347	19671	70675
09/29/2002	15048	20365	14715	50128
	415243	438604	347206	1201053

CHAPTER 5. DATA ANALYSIS

5.1 Introduction

The present chapter contains the findings of this research effort. General database information is presented first, in order to establish relationships between the fundamental traffic flow parameters at the study location (volume, speed, density, free flow speed, peaking characteristics, traffic mix, and number of trucks throughout the day). This is accomplished through general descriptive statistics (frequencies and means) tables and graphs (bar charts, histograms).

Subsequently the analysis focus shifts to testing a number of hypotheses set to examine Heavy Vehicle (HV) influence on freeway traffic operations. A major part of this effort is focused on headways of individual and lagging-leading pairs of vehicles, and the relationship of this variable with other traffic flow parameters, such as speed, volume, truck presence (percent of trucks) and vehicle weight.

5.2 General Study Site Traffic Flow Characteristics

A total of 1,201,053 vehicles were observed during the study period, of which 84.8% were passenger cars (PC) and 9.0% were light trucks. Among heavy vehicles, single-trailer trucks with five axles (vehicle class 9-see Figure 3.1) were the most prevalent at 1.7% and single-trailer trucks with four or less axles (vehicle class 8-see Figure 3.1) were 1.6% of the total vehicle counts. Table 5.1 shows the frequency of each vehicle type in the total vehicle observations.

The average daily volume observed in the analyzed Southbound direction was 70,675 vehicles per day in all three lanes together. Weekday peak hours of traffic were observed generally between 6 am to 9 am and again from 3 pm to 6 pm. During weekends, peak traffic was observed between 11 am and 7 pm. Figures 5.1 and 5.2 stacked bar histograms present weekday and weekend hourly traffic patterns with light vehicles (classes 2 and 3) shown in blue and heavy vehicles (classes 4 and above) shown in green.

TABLE 5.1 Frequencies of vehicles observed at the study site.

	FHWA class	Frequency	Percent	Valid Percent	Cumulative Percent
Motorcycle	1	3,427	.3	.3	.3
PC	2	1,018,981	84.8	84.8	85.1
Four-tire single-unit truck	3	108,584	9.0	9.0	94.2
Buses	4	9,011	.8	.8	94.9
Two-axle, six-tire single-unit truck	5	13,953	1.2	1.2	96.1
Three-axle, single-unit truck	6	6,187	.5	.5	96.6
Four-or-more- axle, single-unit truck	7	290	.0	.0	96.6
Four-or-less axle, single-unit trailer	8	19,694	1.6	1.6	98.3
Five-axle, single trailer	9	20,467	1.7	1.7	100.0
Six-or-more-axle, single trailer	10	91	.0	.0	100.0
Five-or-less-axle, multi-trailer	11	301	.0	.0	100.0
Six-axle, multi-trailer	12	67	.0	.0	100.0
Seven-or-more-axle, multi-trailer	13	2	.0	.0	100.0
Total		1,201,053	100.0	100.0	

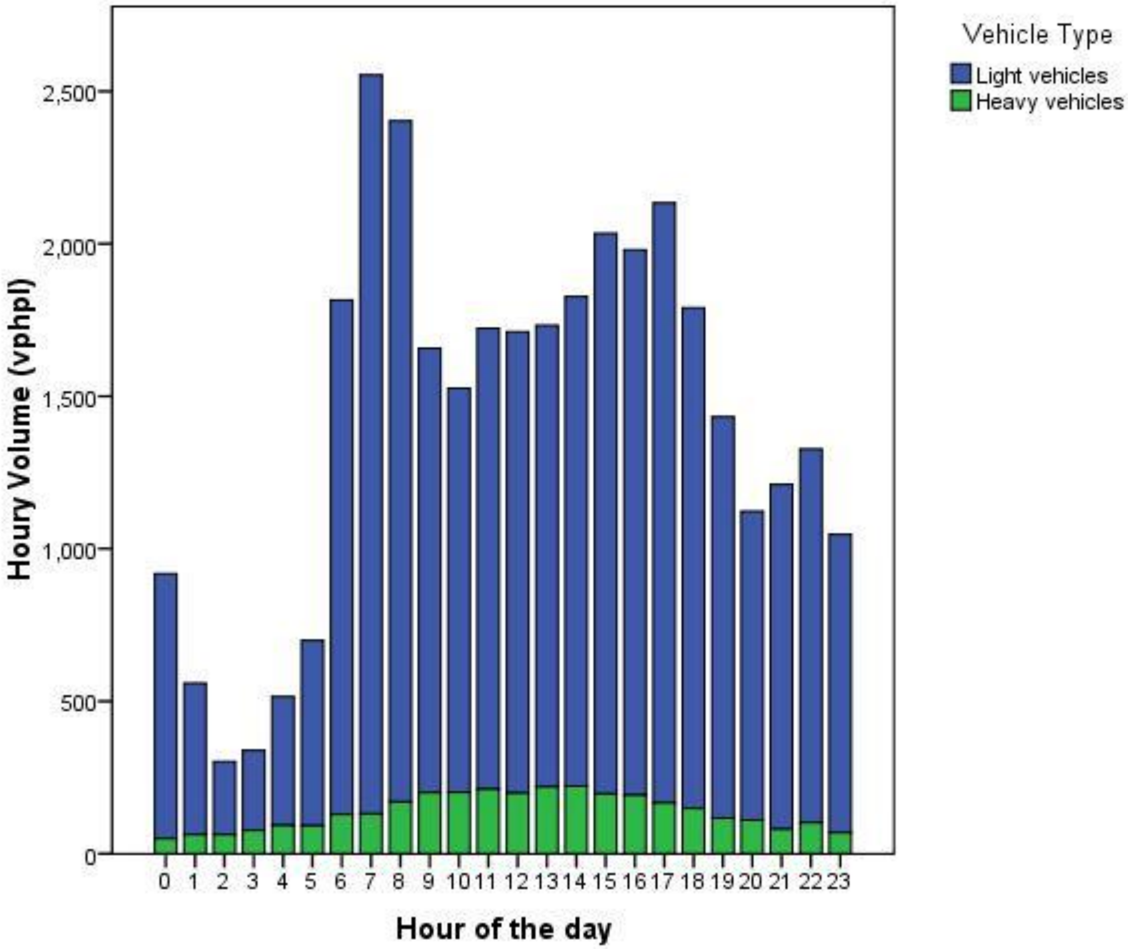

FIGURE 5.1 Weekday hourly traffic distribution.

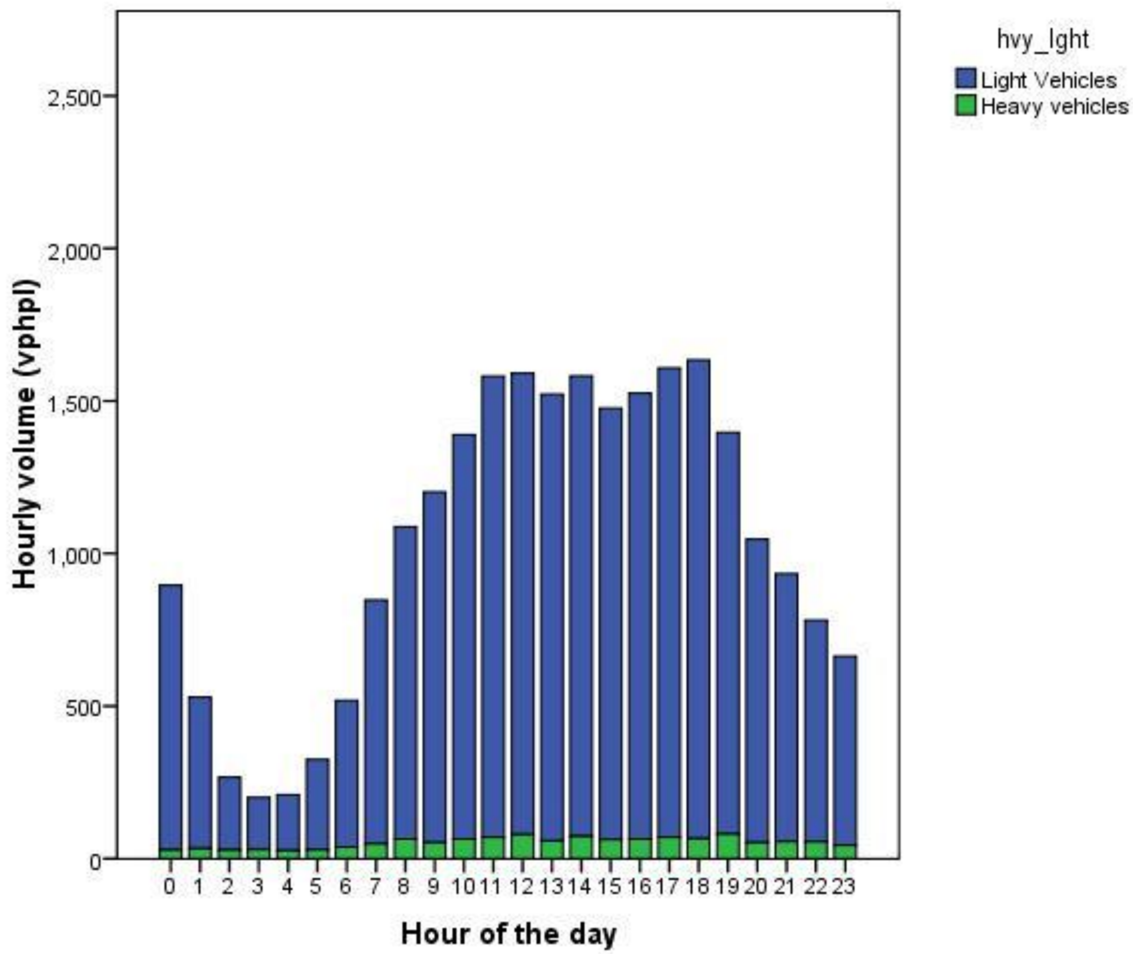

FIGURE 5.2 Weekend hourly traffic distribution.

5.3 Free Flow Speed

According to the HCM 2000, Free-Flow Speed (FFS) is the mean speed of passenger cars measured during low to moderate flows (up to 1,300 pc/h/ln). This average PC speed reflects the net effect of all prevailing geometric conditions, such as lane width, lateral clearance, interchange density, number of lanes, speed limit and vertical and horizontal alignment that influence speed. The HCM 2000 indicates that speed data that include PC and HV can be used to determine FFS for level terrain or moderate downgrades but should not be used for rolling or mountainous terrain (2). As the data for this research was collected from a level freeway segment, the FFS was determined for the mixed traffic stream containing both PC and HV. Figure 5.3 shows the Speed-Volume curve developed for the study site.

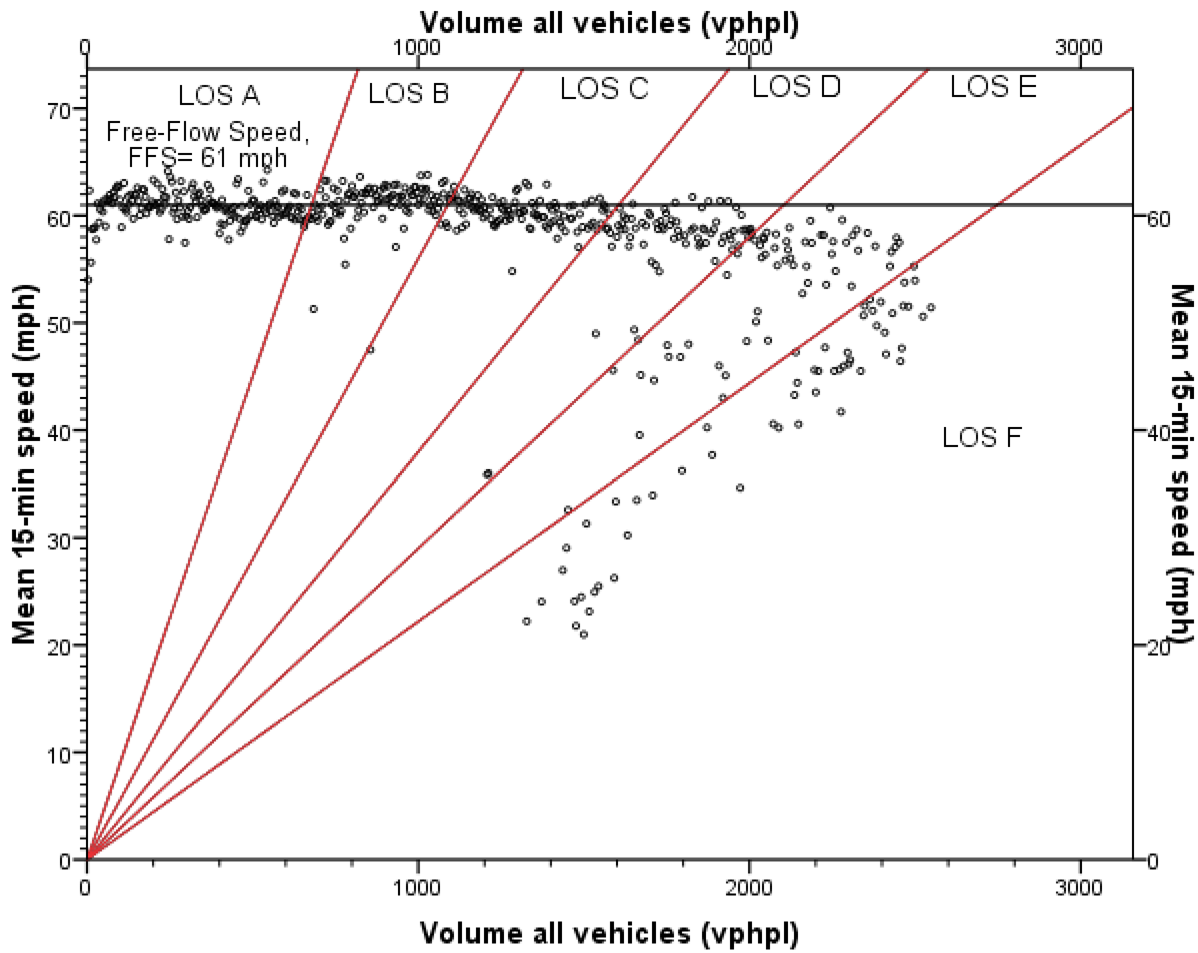

FIGURE 5.3 Vehicle Speed-Volume curve for the study site.

The Speed-Volume curve was developed using hourly per-lane volumes based on average 15-minute flows and the corresponding 15-min average speeds of the mixed traffic stream.

The “rays” (straight lines converging at the origin) of Figure 5.3 indicate the boundaries between Levels of Service (LOS), segregating the collected data into distinct “sectors” for each LOS. Visual inspection reveals that, as congestion levels increase (moving from left-to-right) in Figure 5.3, average speeds start decreasing within LOS C at about 1,200 vphpl.

In order to adhere to the HCM FFS definition intent (the average speed measured at low to moderate flows), speed observations corresponding to flows less than or equal to 1200 vphpl were selected and their average value (61 mph) was considered to be the study location’s FFS (see horizontal line at 61 mph).

The capacity of the study location (based on the highest 15-minute measured flows) was determined to be approximately 2,500 vphpl.

5.4 Headway Relation with Speed

To examine the vehicle headway relation with speed, individual vehicle speeds were divided into 10 speed ranges: 0-10 mph, 10-15 mph, 15-20 mph, 20-25 mph, 25-30 mph, 30-35 mph, 35-40 mph, 40-45 mph, 45-50 mph and greater than 50 mph. The mean headway for each of these speed ranges was calculated. A strong relationship between mean vehicle headway and vehicle speed was identified (r = 0.981 – see Table 5.2). It was found that headway decreased with an increase in vehicle speed and reached its minimum value at a range of 40-45 mph; above 45 mph, headway started increasing with increasing speed. Thus it was documented that the analyzed freeway section reached its capacity (coincident with minimum headways) within the range of 40-45 mph. Figure 5.4 shows average headway relationship with speed.

A regression analysis using average headway as the dependent and speed range as the independent variable had an excellent fit at the 0.000 level of significance (Table 5.3) when a Quadratic equation was fit to the data (see coefficients on Table 5.4 – all regression model coefficients were significant at the 0.000 level). The relation can be expressed by the following equation:

$$Vehicle\ Headway = 0.0018 * Speed^2 + (-0.14) * Speed + 4.94 \qquad \textbf{5.1}$$

Where, Vehicle Headway was measured in seconds.
Vehicle Speed (mid-point of speed range) was measured in mph.

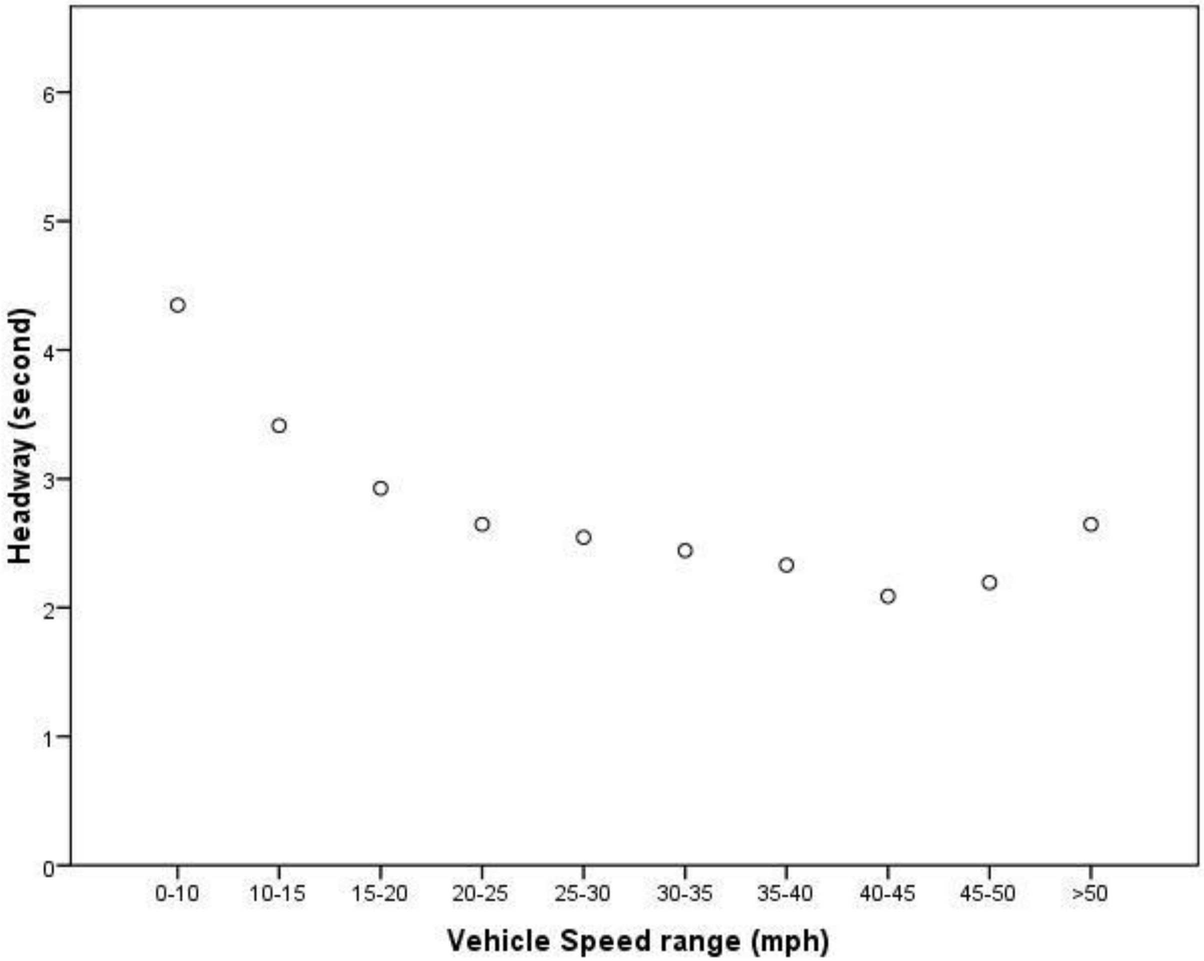

FIGURE 5.4 Average Headway relationship with Vehicle Speed.

TABLE 5.2 Regression model summary of Headway vs. Vehicle speed.

R	R Square	Adjusted R Square	Std. Error of the Estimate
.981	.962	.951	.149

TABLE 5.3 ANOVA results for Headway vs. Vehicle Speed regression analysis.

	Sum of Squares	df	Mean Square	F	Sig.
Regression	3.947	2	1.973	88.787	.000
Residual	.156	7	.022		
Total	4.102	9			

TABLE 5.4 Coefficient values for the Headway vs. Vehicle Speed equation.

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Speed	-.140	.015	-3.152	-9.443	.000
Speed ** 2	0.0018	.000	2.383	7.137	.000
(Constant)	4.935	.187		26.432	.000

5.5 Heavy Vehicle Effect on Lighter Vehicles

A total of 1,200,992 lag-lead vehicle pair observations were available from field data. Enough observations for analysis purposes were available for vehicle pairs involving PC (FHWA class 2), four-tire single-unit trucks (FHWA class 3), four-or-less-axle single-trailer trucks (FHWA class 8) and five-axle single-trailer trucks (FHWA class 9).

A primary hypothesis of this research was that the presence of HV in mixed traffic stream had a negative impact on freeway capacity. This hypothesis was addressed in the present effort in a number of ways, focusing primarily on the effects HV had on headways.

5.5.1 Lagging PC Headways

Previous research efforts determined differences in the headways maintained between specific pairs of vehicle classes. Typically, lighter vehicles were found to maintain larger headways when following (lagging) heavier vehicles than when following other lighter vehicles (4). This finding was tested herein with the available field data. For this effort, lighter vehicles in the database were paired with their leading vehicles. It was desired to test the hypothesis that lighter vehicles would keep longer headways when following a heavier vehicle, than when following another lighter vehicle.

Among the available light vehicle-following-light vehicle pairs, “PC-following-PC” (FHWA vehicle class 2) and “PC-following-four-tire single-unit truck” (FHWA Truck class 3) had a significant presence in the traffic stream.

Among light vehicle-following-heavier vehicle pairs, only “PC-following-four-or-less-axle, single-trailer truck” (FHWA Truck class 8) and “PC-following-five axle, single-trailer truck” (FHWA Truck class 9) pairs had significant numbers of observations for analysis. Table 5.5 shows major lagging-leading vehicle pairs with a lagging PC and the corresponding frequencies.

It was shown earlier that a strong relationship exists between average headway and speed. It was desired to investigate whether headway-speed relationships between particular vehicle class pairs followed this general trend, and whether statistically significant differences existed in headways maintained between particular vehicle classes. The same speed ranges used in section 5.4 to investigate the headway-speed relationship, 0-10 mph, 10-15 mph, 15-20 mph, 20-25 mph, 25-30 mph, 30-35 mph, 35-40 mph, 40-45 mph, 45-50 mph and greater than 50 mph, were used in the present lagging-leading vehicle pair headway investigation, as well. Due to an absence of sufficient observations for PC following trucks class 8 or 9, the speed range 0-10 mph was excluded from the analysis. Only headways equal to or shorter than 10 seconds were included since longer headways are not typically due to vehicle interactions, but, rather, random arrivals under very low volume conditions. Also for speed range 10-15 mph, PC-following-Truck class 9 had only 28 observations. This number was insufficient to provide a representative result for actual field conditions.

An analysis of Variance (ANOVA) of headway (dependent variable) versus Lagging-Leading pair (fixed factor) for each of the ten analyzed speed ranges was used in this investigation. Descriptive statistics, statistical significance and

95% Confidence Intervals (95% CI) for average headway values are shown in Tables 5.6 and 5.7. The 95% headway CI for each vehicle pair type at each analyzed speed range is presented graphically in Figure 5.5.

Table 5.6 shows general headway descriptive statistics for headways maintained between particular vehicle pairs; for example, the average headways between two PC for the speed range of 15-20 mph was 2.65 seconds. The 95% CI for that value was 2.62-2.68 seconds. The average headway for a PC following a truck class 9 within the same speed range was 4.61 seconds with a 95% CI 4.39 to 4.82 seconds. Since the two 95% CI for these two types of Lagging-Leading vehicle pairs did not overlap, the average headway lagging PC maintained from leading trucks class 9 was statistically significantly larger than the average headway they maintained from leading PC at the 95% confidence level.

This same comparison is shown in Table 5.7 for these two vehicle type pairs. In this case headway differences between a Lagging-Leading PC-PC (column (I) Lagging-Leading vehicle pair) and a Lagging-Leading PC-truck class 9 pair (column (J) Lagging-Leading vehicle pair) is shown in column Mean Difference (I-J). In the above example, for the 15-20 mph speed range, the value -1.95 seconds corresponds to the difference 2.65-4.61 seconds (from Table 5.6). The 95% CI for this difference is -2.24 to -1.66 seconds; the difference is statistically significant at the 0.000 level of significance (less than 1/10,000 probability that no difference exists between the two headway populations). Since the 95% CI does not include zero (which would indicate that the two average headways were equal), it can be stated with a high degree of certainty that PC-PC headways are on average 1.95 seconds lower than PC-truck class 9 headways at this speed range.

Within each speed range, the average headways maintained by lagging PC were shortest from leading PC, and progressively increased from leading small trucks class 3, trucks class 8 and trucks class 9.

Findings for individual vehicle classes were consistent with the overall headway-speed observations. Headways decreased with increasing speed with the shortest headways in the 40-45 mph speed range at 1.96 for PC-following-PC, 2.00 seconds for PC-following-small trucks class 3 and 2.35 seconds for PC-following-trucks class 8. The shortest headways for PC-following-trucks class 9 were observed at the 45-50 mph speed range. Headways started increasing as speed kept increasing past the corresponding minimum headway speed ranges.

The level of significance (Sig.) and mean difference (I-J) columns on Table 5.7 in conjunction with the graphical representation of the 95% CI of mean headways in Figure 5.5 lead to the following observations about lagging PC headways:

I. Headways from PC were shorter than headways from small trucks (class 3), however differences were no more than 0.15 seconds at any speed range;

II. Headway differences from PC and small trucks class 3 were not statistically significantly different among themselves (level of significance exceeds 0.141 in most cases but even where statistical significance exists, differences were small and had negligible practical consequences);

III. Headways from heavier vehicles (trucks class 8 and trucks class 9) were statistically significantly higher for all speed ranges. (The only exception was class 8 in the 20-25 mph speed range where 95% PC, truck class 3 and truck class 8 CI overlap);

IV. Headway differences between PC and small trucks class 3 on one hand, and heavier trucks classes 8, 9 on the other, were the longest at the lowest speeds. Headway differences from trucks class 9 decreased with speed; for trucks class 8 the pattern was not consistent with speed.

TABLE 5.5 Types of Lagging-Leading pairs with lagging Passenger Cars (PC) and their frequencies in the dataset.

Lagging-Leading vehicle pair		No. of observations	Percent	Cumulative Percent
Light vehicle-following-Light vehicle	PC-PC	872,100	87.8	87.8
	PC-Small truck class 3	90,113	9.1	96.9
Light vehicle-following-Heavy vehicle	PC-Truck class 8	15,375	1.5	98.5
	PC-Truck class 9	15,339	1.5	100.0
		992,927	100.0	

TABLE 5.6 Headway-Speed relationships for vehicle pairs with Lagging Passenger Cars (PC).

Lagging Vehicle speed range (mph)	Lagging-Leading vehicle pair	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
						Lower Bound	Upper Bound
10-15	PC-PC	2,720	3.18	1.35	.03	3.13	3.23
	PC- Small truck class 3	445	3.33	1.45	.07	3.19	3.46
	PC-Truck class 8	93	4.14	1.55	.16	3.82	4.46
	PC-Truck class 9	28	5.51	1.84	.35	4.80	6.22
15-20	PC-PC	6,443	2.65	1.24	.02	2.62	2.68
	PC-Small truck class 3	1,051	2.78	1.29	.04	2.70	2.86
	PC-Truck class 8	315	2.97	1.71	.10	2.78	3.16
	PC-Truck class 9	131	4.61	1.25	.11	4.39	4.82
20-25	PC-PC	7,557	2.43	1.20	.01	2.40	2.46
	PC-Small truck class 3	1,106	2.50	1.24	.04	2.42	2.57
	PC-Truck class 8	262	2.54	1.45	.09	2.36	2.72
	PC-Truck class 9	161	4.01	1.25	.10	3.81	4.21
25-30	PC-PC	7,470	2.35	1.28	.01	2.32	2.38
	PC-Small truck class 3	1,037	2.38	1.31	.04	2.30	2.46
	PC-Truck class 8	222	2.79	1.46	.10	2.60	2.98
	PC-Truck class 9	145	3.60	1.43	.12	3.37	3.84
30-35	PC-PC	8,324	2.29	1.33	.01	2.26	2.31
	PC-Small truck class 3	1,067	2.33	1.33	.04	2.25	2.41
	PC-Truck class 8	206	2.52	1.38	.10	2.33	2.71
	PC-Truck class 9	141	3.12	1.12	.09	2.93	3.30
35-40	PC-PC	10,253	2.18	1.39	.01	2.15	2.21
	PC-Small truck class 3	1,121	2.26	1.39	.04	2.17	2.34
	PC-Truck class 8	193	2.62	1.47	.11	2.41	2.83
	PC-Truck class 9	143	2.93	1.29	.11	2.71	3.14
40-45	PC-PC	17,516	1.96	1.33	.01	1.94	1.98
	PC-Small truck class 3	1,725	2.00	1.38	.03	1.94	2.07
	PC-Truck class 8	322	2.35	1.38	.08	2.20	2.50
	PC-Truck class 9	230	2.77	1.27	.08	2.60	2.93
45-50	PC-PC	45,633	2.06	1.66	.01	2.05	2.08
	PC-Small truck class 3	4,562	2.03	1.63	.02	1.98	2.07
	PC-Truck class 8	919	2.49	1.64	.05	2.38	2.59
	PC-Truck class 9	785	2.62	1.55	.06	2.51	2.73
>50	PC-PC	691,379	2.60	2.06	.00	2.59	2.60
	PC-Small truck class 3	70,715	2.56	2.05	.01	2.54	2.57
	PC-Truck class 8	11,279	2.87	2.01	.02	2.83	2.91
	PC-Truck class 9	11,614	3.11	1.94	.02	3.07	3.14

TABLE 5.7 Types of Lagging-Leading vehicle pairs with Lagging Passenger Cars (PC).

Lagging Vehicle speed range(mph)	(I) Lagging-Leading vehicle pair	(J) Lag-Leading vehicle pair	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
10-15	PC-PC	PC-Small truck class 3	-0.15	0.07	0.141	-0.33	0.03
		PC-Truck class 8	-0.96	0.14	0.000	-1.33	-0.59
		PC-Truck class 9	-2.33	0.26	0.000	-3.00	-1.66
15-20	PC-PC	PC-Small truck class 3	-0.13	0.04	0.014	-0.24	-0.02
		PC-Truck class 8	-0.32	0.07	0.000	-0.50	-0.13
		PC-Truck class 9	-1.95	0.11	0.000	-2.24	-1.66
20-25	PC-PC	PC-Small truck class 3	-0.07	0.04	0.301	-0.17	0.03
		PC-Truck class 8	-0.11	0.08	0.454	-0.31	0.08
		PC-Truck class 9	-1.58	0.10	0.000	-1.83	-1.33
25-30	PC-PC	PC-Small truck class 3	-0.03	0.04	0.933	-0.14	0.08
		PC-Truck class 8	-0.44	0.09	0.000	-0.66	-0.21
		PC-Truck class 9	-1.25	0.11	0.000	-1.53	-0.98
30-35	PC-PC	PC-Small truck class 3	-0.05	0.04	0.674	-0.16	0.06
		PC-Truck class 8	-0.23	0.09	0.060	-0.47	0.01
		PC-Truck class 9	-0.83	0.11	0.000	-1.12	-0.54
35-40	PC-PC	PC-Small truck class 3	-0.08	0.04	0.286	-0.19	0.03
		PC-Truck class 8	-0.44	0.10	0.000	-0.70	-0.18
		PC-Truck class 9	-0.75	0.12	0.000	-1.05	-0.45
40-45	PC-PC	PC-Small truck class 3	-0.05	0.03	0.492	-0.13	0.04
		PC-Truck class 8	-0.39	0.07	0.000	-0.59	-0.20
		PC-Truck class 9	-0.81	0.09	0.000	-1.04	-0.58
45-50	PC-PC	PC-Small truck class 3	0.03	0.03	0.554	-0.03	0.10
		PC-Truck class 8	-0.43	0.06	0.000	-0.57	-0.29
		PC-Truck class 9	-0.56	0.06	0.000	-0.71	-0.41
>50	PC-PC	PC-Small truck class 3	0.04	0.01	0.001	0.01	0.06
		PC-Truck class 8	-0.26	0.02	0.000	-0.32	-0.21
		PC-Truck class 9	-0.47*	0.02	0.000	-0.53	-0.42

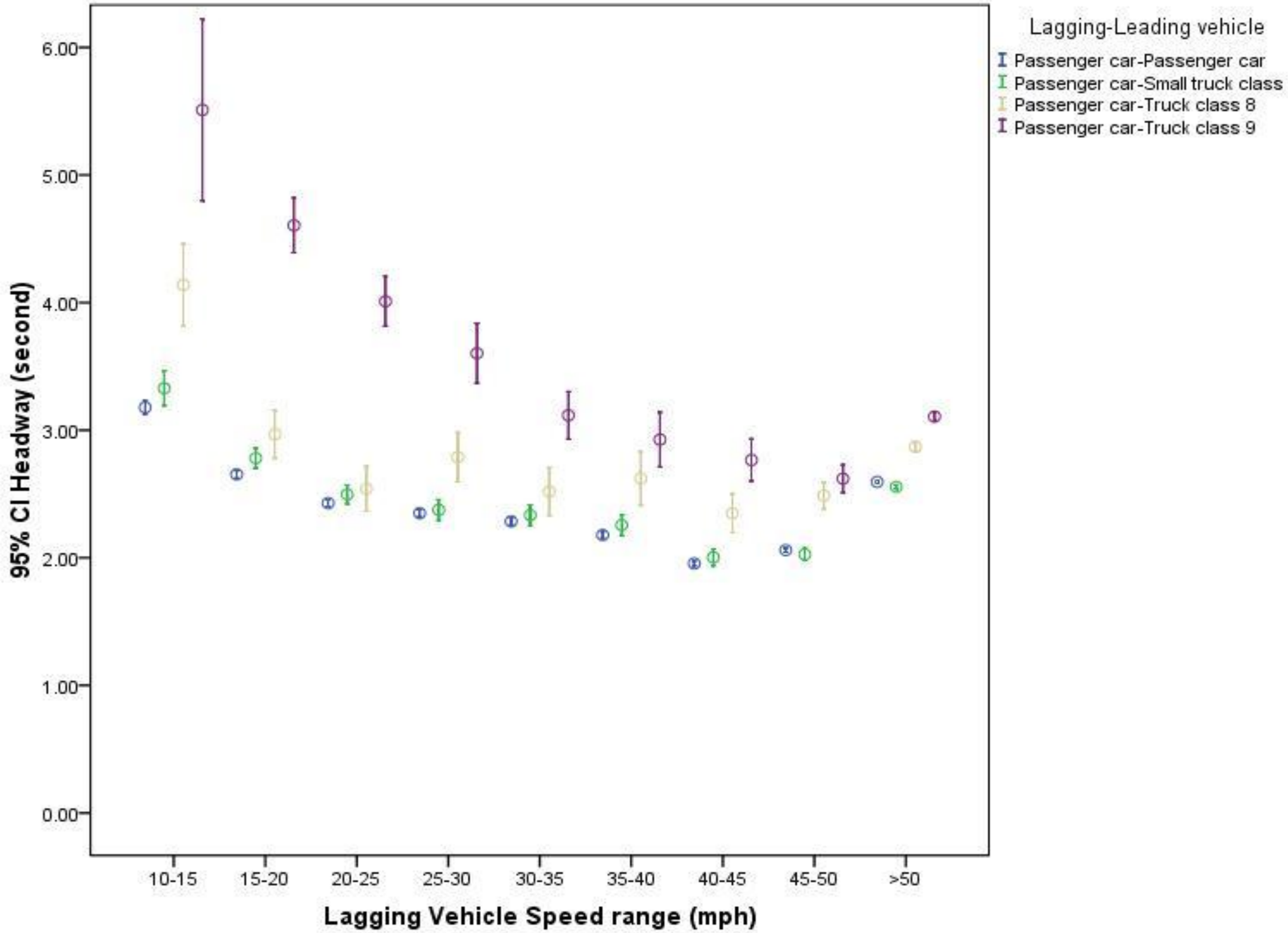

FIGURE 5.5 95% mean Headway Confidence Intervals for Lagging-Leading vehicle pairs with Lagging Passenger Cars (PC) within specific speed ranges.

5.5.2 Passenger car-Heavy Vehicle Pair Headways

Although headway differences were identified in the literature depending on whether a PC leads or lags a HV, there was no agreement among researchers about the direction of these differences. HV following (lagging) PC was found to maintain larger headways than PC following HV (6, 10). However, another study found that HV traveled closer to PC than PC following HV (9).

Given the ambiguity of previous findings, it was desired to provide answers based on the study database. Furthermore, given the already documented strong headway-speed relationship, it was desired to identify any statistically significant headway differences and quantify their magnitudes within each of the previous defined speed ranges.

Headway differences depending on whether a PC leads or lags a HV were tested for two HV classes, trucks class 8 and class 9. Two separate hypotheses were examined. The first tested for statistically significant headway differences between PC leading or lagging a truck class 8; the second examined a similar hypothesis for trucks class 9.

The mean headway for all examined vehicle combinations was analyzed for the following nine vehicle speed ranges: 10-15 mph, 15-20 mph, 20-25 mph, 25-30 mph, 30-35 mph, 35-40 mph, 40-45 mph, 45-50 mph and greater than 50 mph. Not enough data were available for the 0-10 mph speed range; headways greater than 10 seconds were excluded because they were not due to vehicle interactions, but, rather, random arrivals under very low volume conditions.

An Analysis of Variance (ANOVA) of headway (dependent variable) versus

Lagging-Leading pair (fixed factor) for each of the nine analyzed speed ranges was used to address each of the two hypotheses. Headway descriptive statistics (number of cases, mean, standard deviations and standard error) as well as 95% Confidence Intervals (95% CI) for means are provided on Table 5.8. The 95% CI for headway means involving trucks class 8 are graphically depicted in Figure 5.6; Figure 5.7 shows similar information for trucks class 9.

The numeric values of the upper and lower bounds of the 95% CI depicted in Figure 5.6 can be found in Table 5.8. For example, in the 10-15 mph speed range, the lower and upper bounds for PC following trucks class 8 are 3.82 and 4.46 seconds, respectively; for trucks class 8 following PC they are 3.59 and 4.58 seconds, respectively. Since the 95% headway CI for these two Lagging-Leading vehicle pairs overlap, the corresponding means (4.14 and 4.09 seconds) are not statistically significantly different (see overlapping blue (PC) and green (trucks class 8) confidence intervals for the 10-15 mph speed range on Figure 5.6). However, lagging trucks class 8 had statistically significant higher mean headways than lagging PC for all other examined speed ranges. A similar pattern of statistically significant differences was found for lagging trucks class 9, compared to lagging PC, but significant differences started at the 20-25 mph speed range-see Figure 5.7.

TABLE 5.8 Average value and the 95% Confidence Interval of Headway (second) for different Passenger Cars (PC)- Semi trucks lagging-leading pair.

Lagging Vehicle speed range (mph)	Lagging-Leading vehicle pair	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
						Lower Bound	Upper Bound
10-15	PC-Truck class 8	93	4.14	1.55	.16	3.82	4.46
	PC-Truck class 9	28	5.51	1.84	.35	4.80	6.22
	Truck class 8-PC	53	4.09	1.79	.25	3.59	4.58
	Truck class 9-PC	23	5.36	1.97	.41	4.51	6.21
15-20	PC-Truck class 8	315	2.97	1.71	.10	2.78	3.16
	PC-Truck class 9	131	4.61	1.25	.11	4.39	4.82
	Truck class 8-PC	338	3.50	1.70	.09	3.32	3.68
	Truck class 9-PC	130	4.66	1.98	.17	4.31	5.00
20-25	PC-Truck class 8	262	2.54	1.45	.09	2.36	2.72
	PC-Truck class 9	161	4.01	1.25	.10	3.81	4.21
	Truck class 8-PC	294	3.44	1.89	.11	3.22	3.66
	Truck class 9-PC	156	4.77	2.13	.17	4.44	5.11
25-30	PC-Truck class 8	222	2.79	1.46	.10	2.60	2.98
	PC-Truck class 9	145	3.60	1.43	.12	3.37	3.84
	Truck class 8-PC	210	3.53	1.94	.13	3.27	3.80
	Truck class 9-PC	147	4.28	1.93	.16	3.96	4.59
30-35	PC-Truck class 8	206	2.52	1.38	.10	2.33	2.71
	PC-Truck class 9	141	3.12	1.12	.09	2.93	3.30
	Truck class 8-PC	169	3.57	2.11	.16	3.25	3.89
	Truck class 9-PC	129	4.04	1.96	.17	3.70	4.38
35-40	PC-Truck class 8	193	2.62	1.47	.11	2.41	2.83
	PC-Truck class 9	143	2.93	1.29	.11	2.71	3.14
	Truck class 8-PC	164	3.38	1.98	.15	3.07	3.68
	Truck class 9-PC	172	3.54	1.76	.13	3.28	3.81
40-45	PC-Truck class 8	322	2.35	1.38	.08	2.20	2.50
	PC-Truck class 9	230	2.77	1.27	.08	2.60	2.93
	Truck class 8-PC	274	3.05	1.89	.11	2.82	3.27
	Truck class 9-PC	246	3.49	1.91	.12	3.25	3.73
45-50	PC-Truck class 8	919	2.49	1.64	.05	2.38	2.59
	PC-Truck class 9	785	2.62	1.55	.06	2.51	2.73
	Truck class 8-PC	598	3.03	1.98	.08	2.87	3.19
	Truck class 9-PC	1143	3.53	2.11	.06	3.40	3.65
>50	PC-Truck class 8	11279	2.87	2.01	.02	2.83	2.91
	PC-Truck class 9	11614	3.11	1.94	.02	3.07	3.14
	Truck class 8-PC	11822	3.12	2.15	.02	3.08	3.16
	Truck class 9-PC	11230	3.30	2.10	.02	3.26	3.33

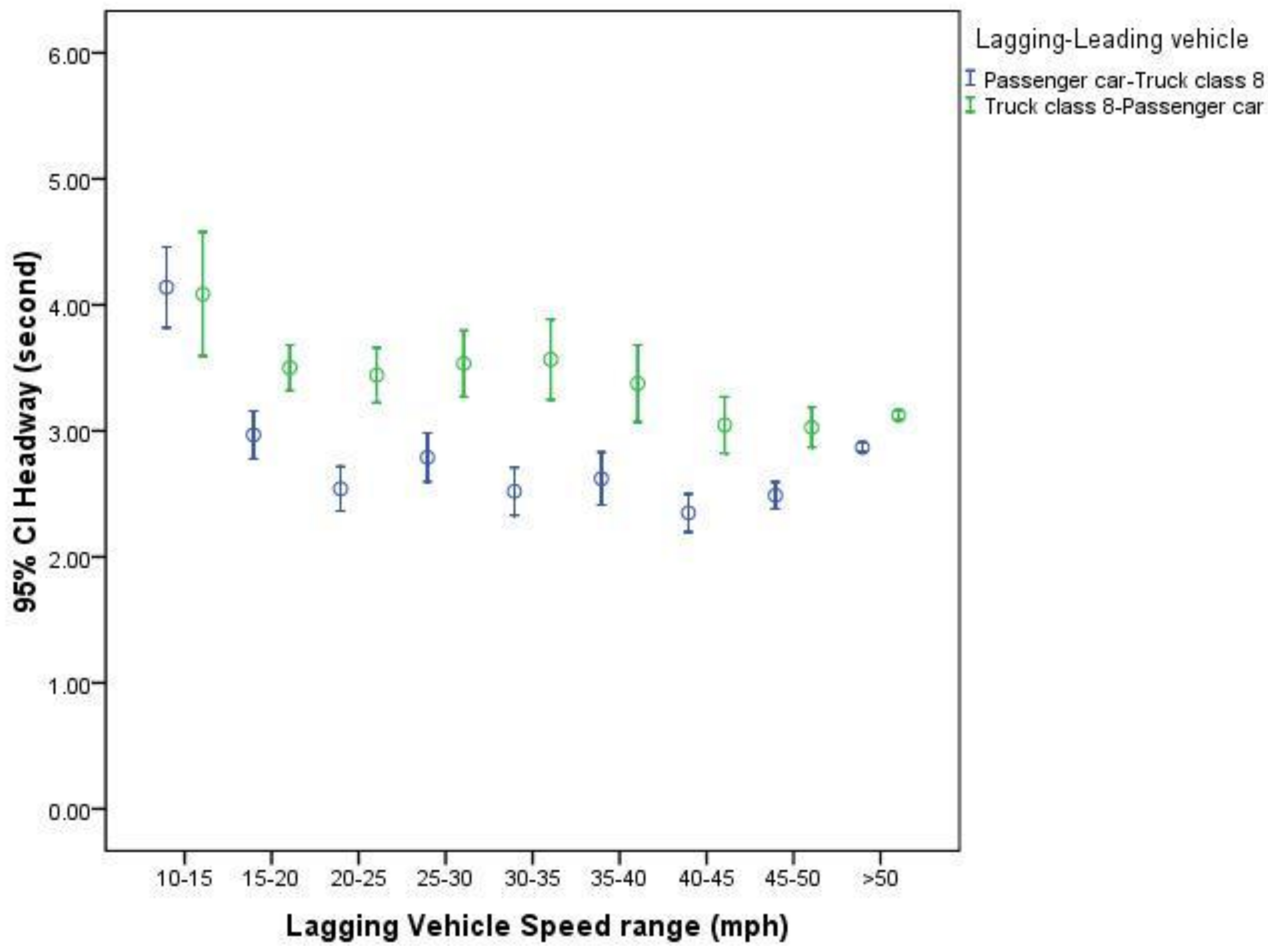

FIGURE 5.6 95% mean Headway Confidence Intervals for Passenger Cars-following-Trucks class 8 and Trucks class 8-following- Passenger Cars within specified speed ranges.

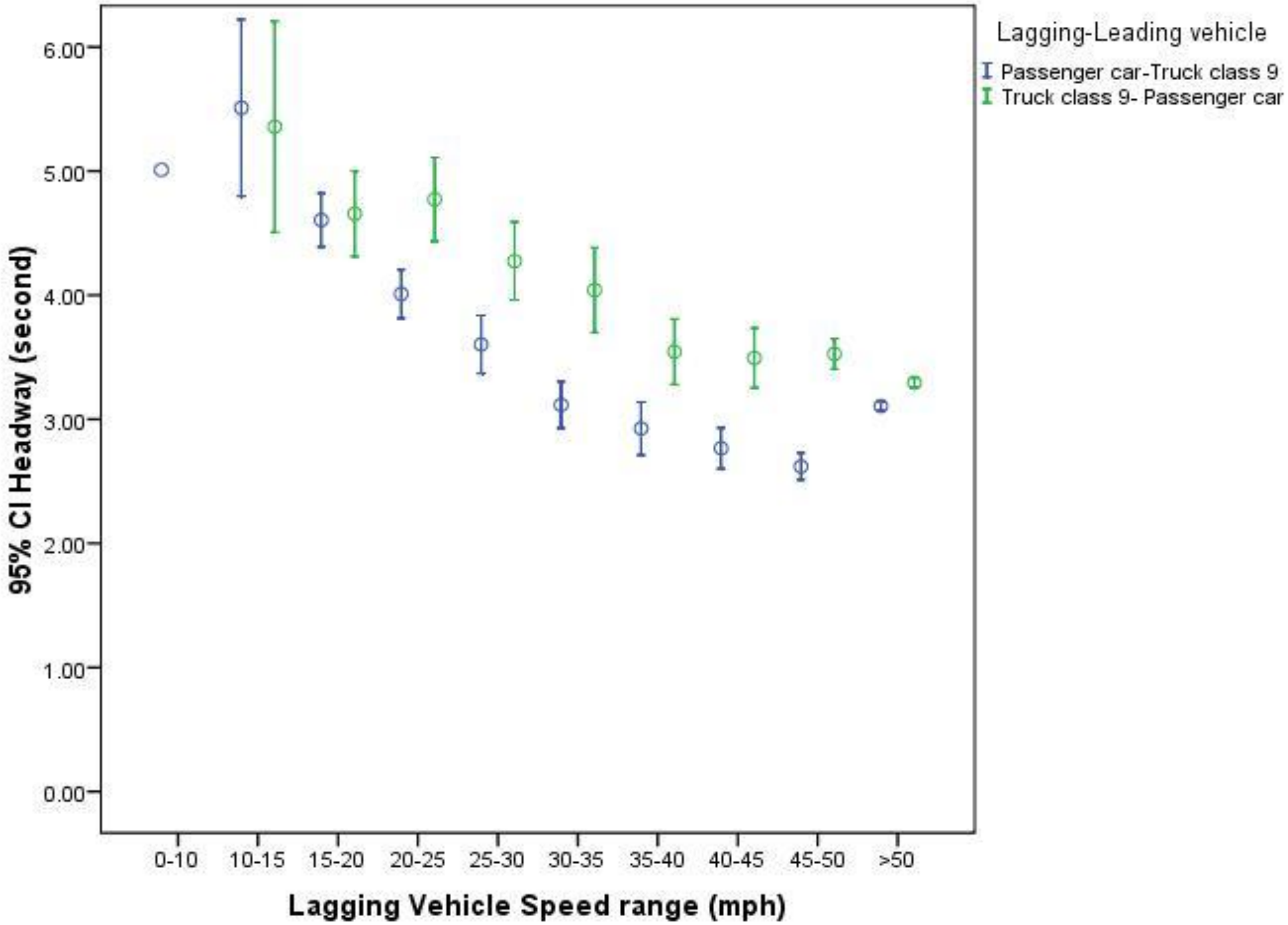

FIGURE 5.7 95% mean Headway Confidence Intervals for Passenger Cars-following-Trucks class 9 and Trucks class 9-following- Passenger Cars within specific speed ranges.

5.5.3 Gross Vehicle Weight-Headway Relation

The preceding section addressed PC-HV pairs in the traffic stream. It documented that lagging larger vehicle drivers (classes 8 and 9) maintain longer headways than lagging PC drivers. The heaviest analyzed vehicles (class 9) maintained the longest headways thus a basic vehicle weight-headway relationship was evident (the heavier the lagging vehicle, the longer the headways). This relationship seems reasonable, since heavier vehicles need longer distances to decelerate, thus their drivers choose to maintain longer headways in order to have adequate deceleration/stopping distances.

The relationship between vehicle class and vehicle weight is not straight-forward, however, due to the effect of payload on the overall vehicle weight (Gross Vehicle Weight-GVW). For PC, the maximum payload amounts to about 20% of the empty vehicle weight. For vehicle classes 3-6, maximum payloads may amount to as much as 50% to 100% of the empty vehicle weight; for semi trucks (classes 8 and 9) maximum payload may be up to 200% of their empty weight. For example, a class 8 vehicle empty weight ranges from 20-26 kips with a maximum payload of 54 kips and a maximum GVW of 80 kips.

Thus, a loaded class 8 vehicle may exceed the typical weight of an empty class 9 vehicle. This example leads to the observation that, if headways are decided based on maintaining safe deceleration/stopping distances, which in turn depend on vehicle weight, it is GVW rather than vehicle class that should be used as an explanatory variable for heavy vehicle headways.

The present section analyzes the relationship between GVW and headways for each of the nine vehicle speed ranges used in previous sections. The underlying assumption in this analysis is that lagging vehicle drivers choose headways depending on their own vehicle braking needs-they maintain longer distances when loaded than when empty-rather than based on the leading vehicle class.

Three GVW ranges were used for this analysis: 0-15 kips (light vehicles), 15-30 kips (medium weight vehicles), and more than 30 kips (heavy vehicles). Analysis of Variance was performed using headway as the dependent variable and speed ranges and the above-defined GVW ranges as fixed factors. Descriptive statistics, as well as the upper and lower bounds of the 95% headway Confidence Intervals (95% CI) are presented in Table 5.9. Figure 5.8 provides a graphical presentation of the 95% headway CI.

The previously identified trend of decreasing headways with increasing speeds was evident here as well, for each of the three analyzed GVW ranges. Minimum headways were associated with the 40-45 mph speed range for light and medium weight vehicles; minimum headways for heavy vehicles were observed in the greater than 50 mph speed range.

Headway increased with GVW within each analyzed speed range, as expected. Light vehicle headways were statistically significantly shorter than those of medium weight vehicles, which in turn were shorter than heavy vehicle headways; however headway differences between medium weight and heavy vehicles were not statistically significantly different for the following speed ranges: 10-15 mph, 35-40 mph and 45-50 mph, as can be concluded from their overlapping 95% CI values shown numerically on Table 5.9 and graphically in Figure 5.8.

Headway differences between heavy and light vehicles were the longest at low speeds and decreased with increasing speed (Figure 5.8).

TABLE 5.9 Headway relations with Speed and GVW.

Vehicle speed range (mph)	Gross vehicle weight (Kips)		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
							Lower Bound	Upper Bound
10-15	Light	0-15	4,421	3.34	1.49	.02	3.29	3.38
	Medium	15-30	91	4.83	1.92	.20	4.43	5.23
	Heavy	>30	85	5.28	1.77	.19	4.90	5.66
15-20	Light	0-15	10,262	2.79	1.33	.01	2.77	2.82
	Medium	15-30	331	3.89	1.74	.10	3.70	4.08
	Heavy	>30	481	5.03	1.96	.09	4.85	5.20
20-25	Light	0-15	11,399	2.53	1.26	.01	2.50	2.55
	Medium	15-30	315	3.71	1.71	.10	3.52	3.89
	Heavy	>30	472	4.68	2.01	.09	4.49	4.86
25-30	Light	0-15	10,979	2.43	1.31	.01	2.40	2.45
	Medium	15-30	277	3.72	1.90	.11	3.50	3.95
	Heavy	>30	478	4.50	1.94	.09	4.32	4.67
30-35	Light	0-15	11,692	2.35	1.35	.01	2.32	2.37
	Medium	15-30	282	3.61	1.85	.11	3.39	3.83
	Heavy	>30	426	4.21	1.99	.10	4.02	4.40
35-40	Light	0-15	13,652	2.25	1.41	.01	2.22	2.27
	Medium	15-30	303	3.55	1.96	.11	3.33	3.78
	Heavy	>30	486	3.81	1.88	.09	3.64	3.98
40-45	Light	0-15	22,709	2.01	1.36	.01	1.99	2.03
	Medium	15-30	507	3.30	1.96	.09	3.13	3.47
	Heavy	>30	700	3.68	1.92	.07	3.53	3.82
45-50	Light	0-15	59,802	2.11	1.67	.01	2.09	2.12
	Medium	15-30	1,655	3.41	2.09	.05	3.31	3.51
	Heavy	>30	2,521	3.50	2.05	.04	3.42	3.58
>50	Light	0-15	897,395	2.62	2.06	.00	2.61	2.62
	Medium	15-30	12,404	3.27	2.14	.02	3.24	3.31
	Heavy	>30	29,413	3.34	2.08	.01	3.32	3.37

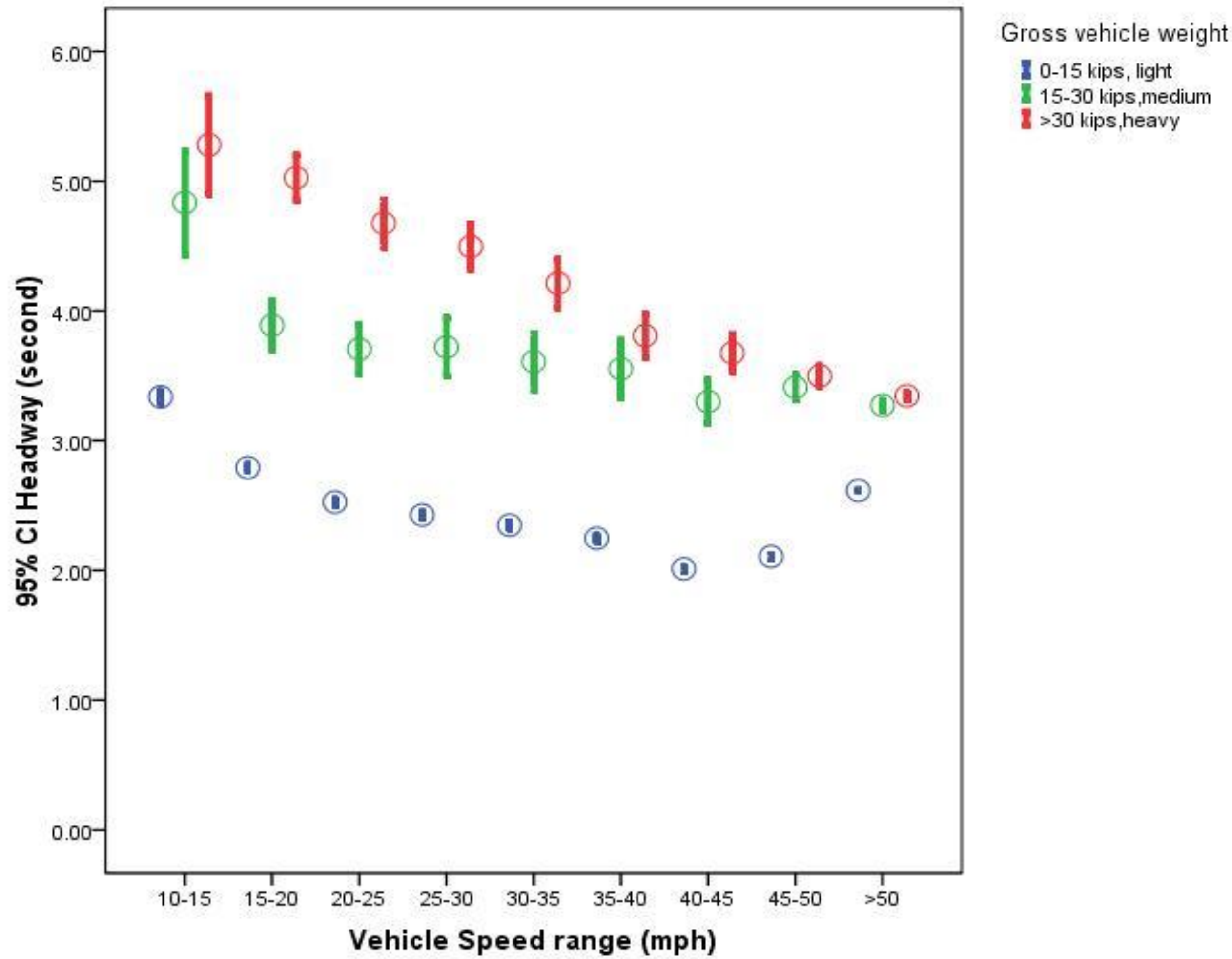

FIGURE 5.8 95**%** mean Headway Confidence Intervals for Gross Vehicle Weight Categories (in kips) within specific speed ranges.

5.6 Heavy Vehicle Percentage and Passenger Car Equivalent Factor Relationship

One objective of this thesis was to identify the effect of congestion on the Passenger Car Equivalent (PCE) factor. The following paragraphs describe the methodology used to calculate the PCE factor based on the available data for which Speed-Volume and Level of Service (LOS) relations at the analyzed location are presented on Figure 5.9.

Previous research efforts determined that PCE values decrease with an increasing percentage of heavy vehicles in the mixed traffic stream (11). It was desired to test if this finding held true in the study database.

Since information on PC and HV headways was readily available from the database, it was decided to use equation ***2.1*** to directly calculate the PCE value. Thus PCE was calculated as the ratio of average HV headway divided by average PC headway. Both numerator and denominator values represented headways at, or near capacity.

The denominator was calculated based on PC-only traffic (Figure 5.10). The figure presents 315 hours of PC-only traffic (3,781 five-minute) observations. Each observation is the ordered (x,y) pair of an equivalent hourly volume (five-minute flow multiplied by 12) and the corresponding five-minute average speed. (HCM 2000 capacity figures are based on 15-minute minute observations. Five-minute observations were used herein because no fifteen-minute period was free of truck presence in the analyzed database.) A value reasonably close to the minimum PC-to-PC headway (headway at capacity) was used for the denominator of all PCE calculations in the present section. This value represented the “ideal” headway under which the maximum throughput occurred at the study location.

HV effect on capacity was evaluated by first evaluating PC and HV headways at capacity for each of four separate truck presence levels: greater than 0% but less than 3% truck presence, 3-6%, 6-9% and more than 9%. (These levels represented truck presence quartiles at the analyzed location.) Subsequently, PCE factors were evaluated by forming the ratio of the newly calculated headways over the headway at capacity in PC-only traffic.

Figures 5.11 through 5.14 provide speed-volume and LOS relationships for the four truck presence levels defined in the previous paragraph, in the same order. The number of data collection hours represented in these figures ranged from a low of 177 to a high of 339.

A visual inspection reveals that the maximum throughput in the PC-only Figure 5.10 was lower than the maximum throughput in Figure 5.11 where small percentages of trucks (up to 3%) were present in each analyzed 5-minute period. This was probably due to the fact that the highest throughput occurred during the morning peak period (see weekday peaking behavior in Figure 5.1), when truck presence was inevitable, even during periods as short as five-minutes. This observation is reinforced by the scarcity of LOS E and LOS F observations in Figure 5.10 compared to all other speed-volume figures in this section.

In contrast, Figure 5.11 contains a significant number of observations at these two LOS, indicating that the freeway operated under these conditions for a significant length of time; the capacity value was higher here than the one in Figure 5.10. [That is, the minimum PC-to-PC headway (corresponding to operation at capacity) was lower in Figure 5.11.] The lack of sustained operation at LOS E and F for a significant length of time was a weakness of the analyzed database (in the sense that it did not allow the calculation of a PC-to-PC headway at capacity in a “pure” PC traffic stream) and was due to the peaking characteristics at the analyzed location.

Maximum throughput became progressively lower in Figures 5.12, 5.13 and 5.14. As percent trucks in the traffic stream increased, operation at LOS E and F became more frequent and operation at LOS F occurred at lower speeds.

Derivation of PCE values focused on the parts of Figures 5.11 through 5.14 representing operation under the most congested conditions, when per lane volumes were at, or above the 2,000 vphpl level. Average PC and HV headways were calculated for each such data subset in Figures 5.11 through 5.14. Separate HV statistics were compiled for vehicles classes 8 and 9 (single-trailer semi trucks) and collectively for all vehicles in classes 4 and above. The percent HV in Figures 5.11 through 5.14 was based on the collective presence of vehicles class 4 and above.

This information is presented in Table 5.10. PCE values were then determined by dividing these headways by the minimum PC headway in a PC-only stream (Figure 5.10), determined to be 1.43 seconds. (This value is conservative as explained above, since lower PC-to-PC headways—less than 1.40 seconds-- were found when truck percentage was greater than zero and up to 3%.)

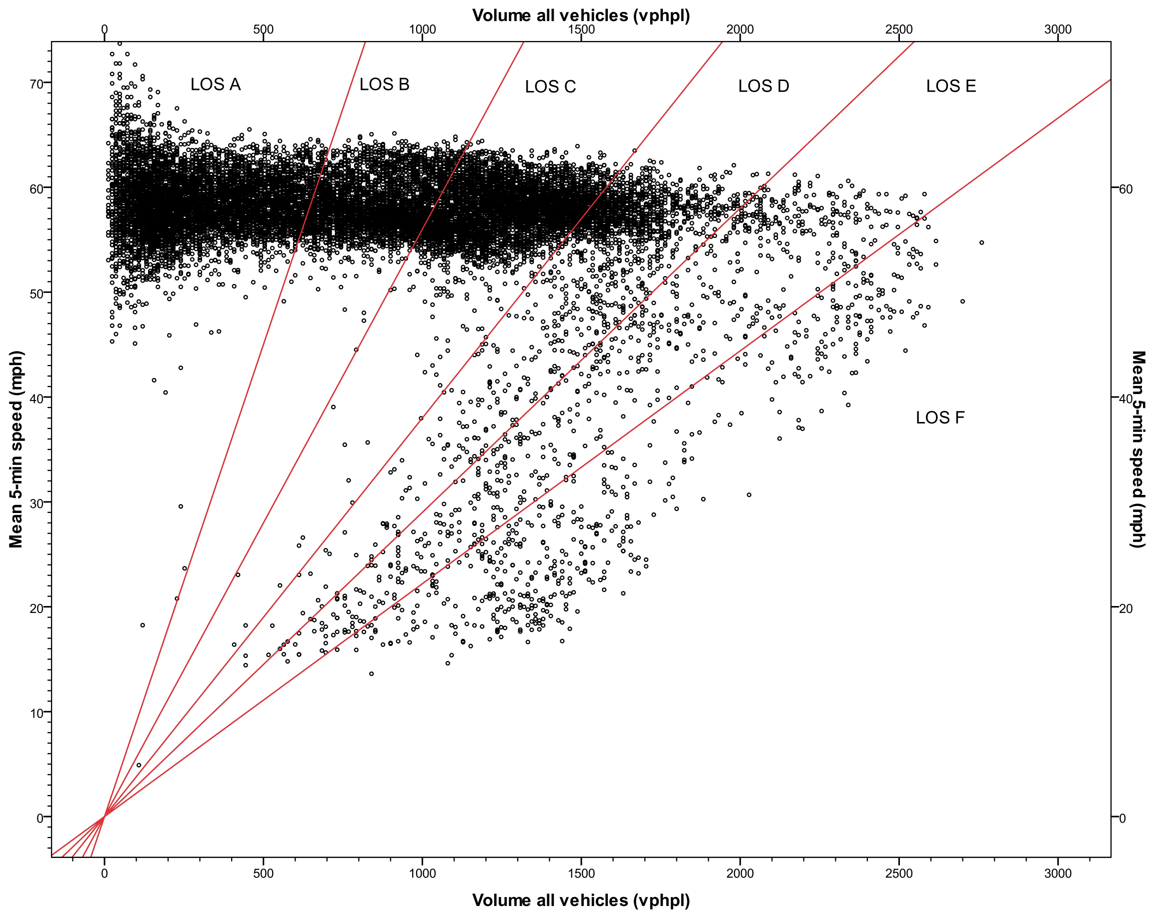

FIGURE 5.9 Speed-volume and LOS relationships-all vehicles.

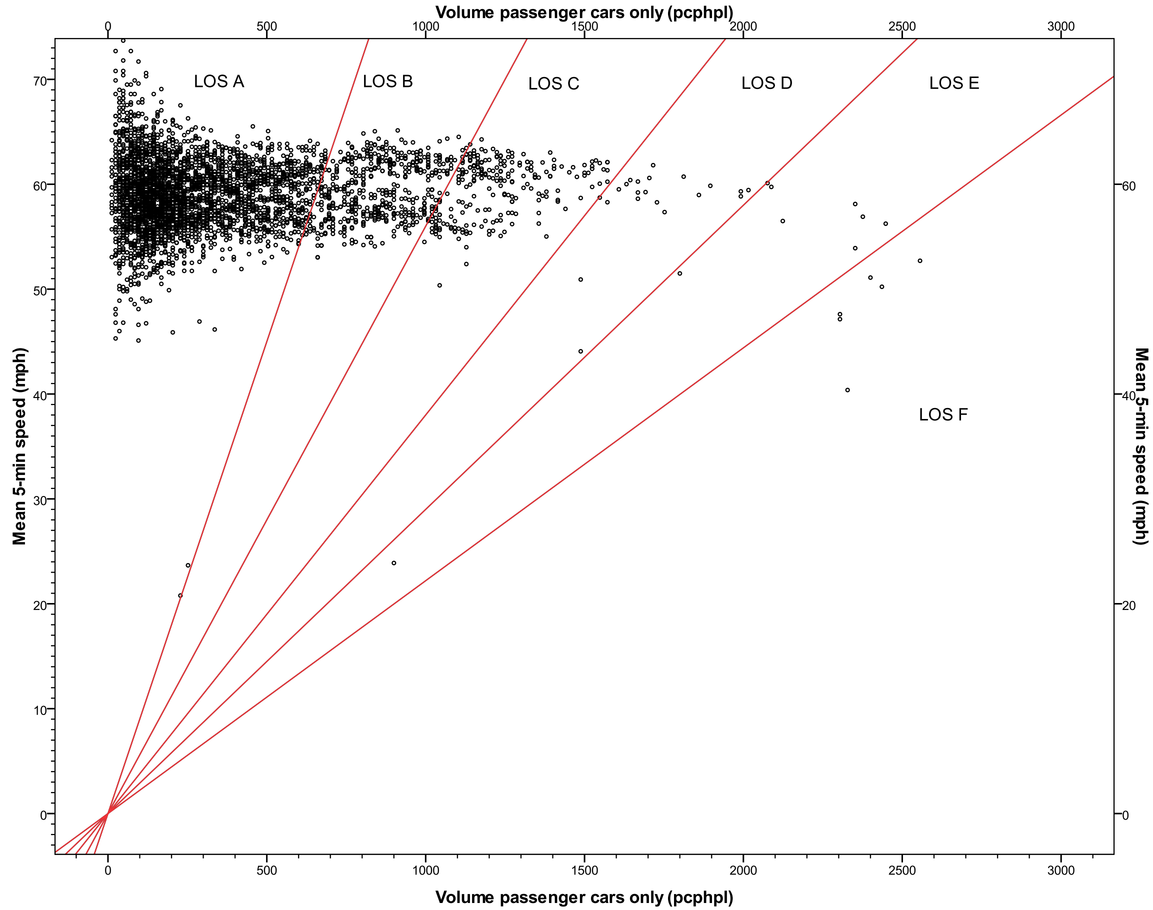

FIGURE 5.10 Speed-volume and LOS relationships-passenger cars only.

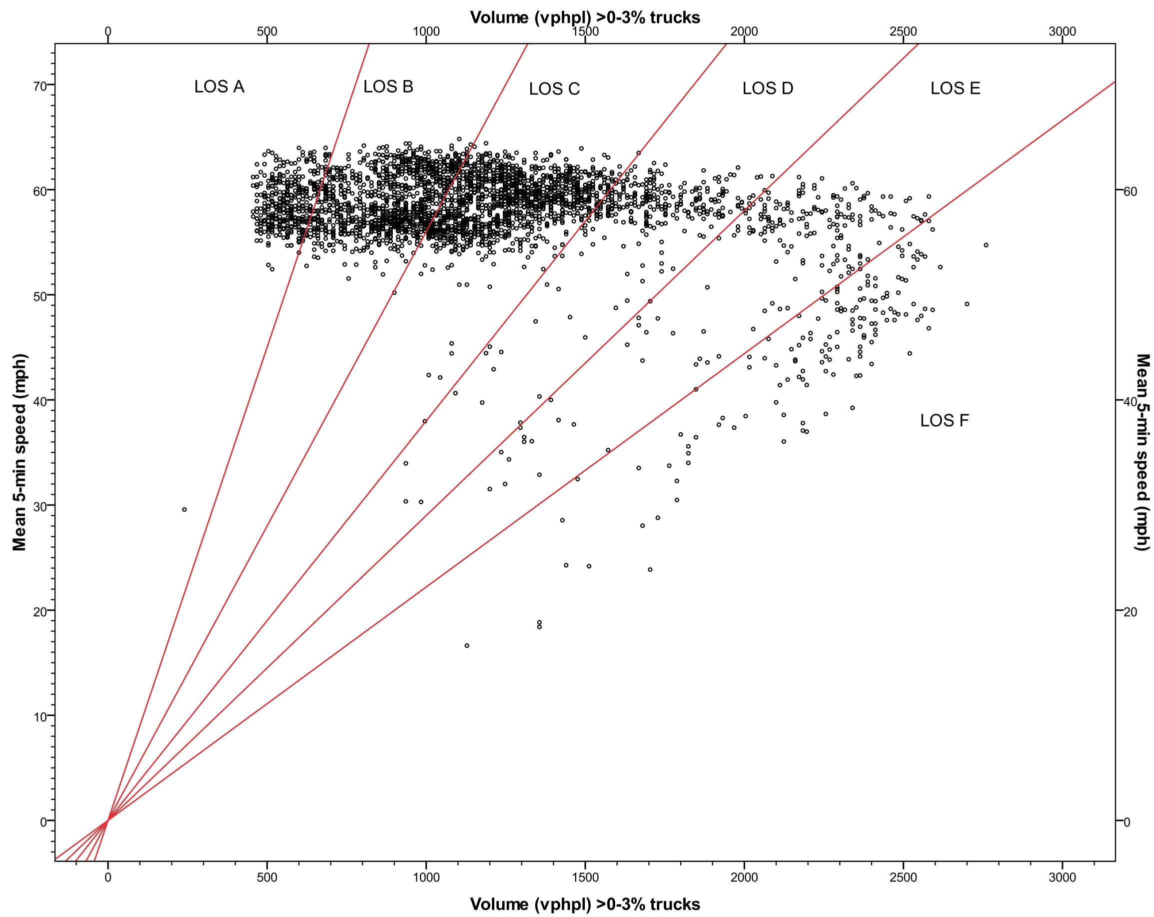

FIGURE 5.11 Speed-volume and LOS relationships-trucks present-up to 3% trucks.

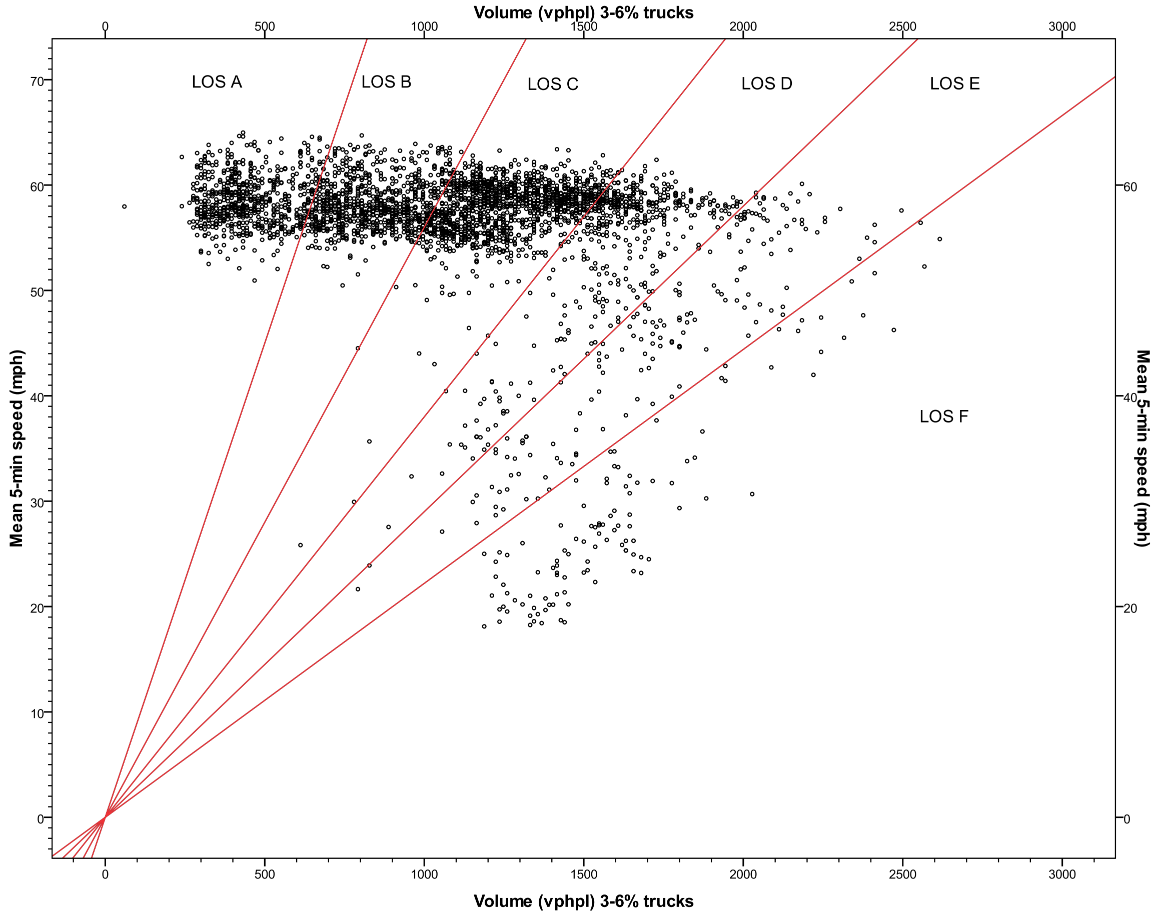

FIGURE 5.12 Speed-volume and LOS relationships- 3-6% trucks.

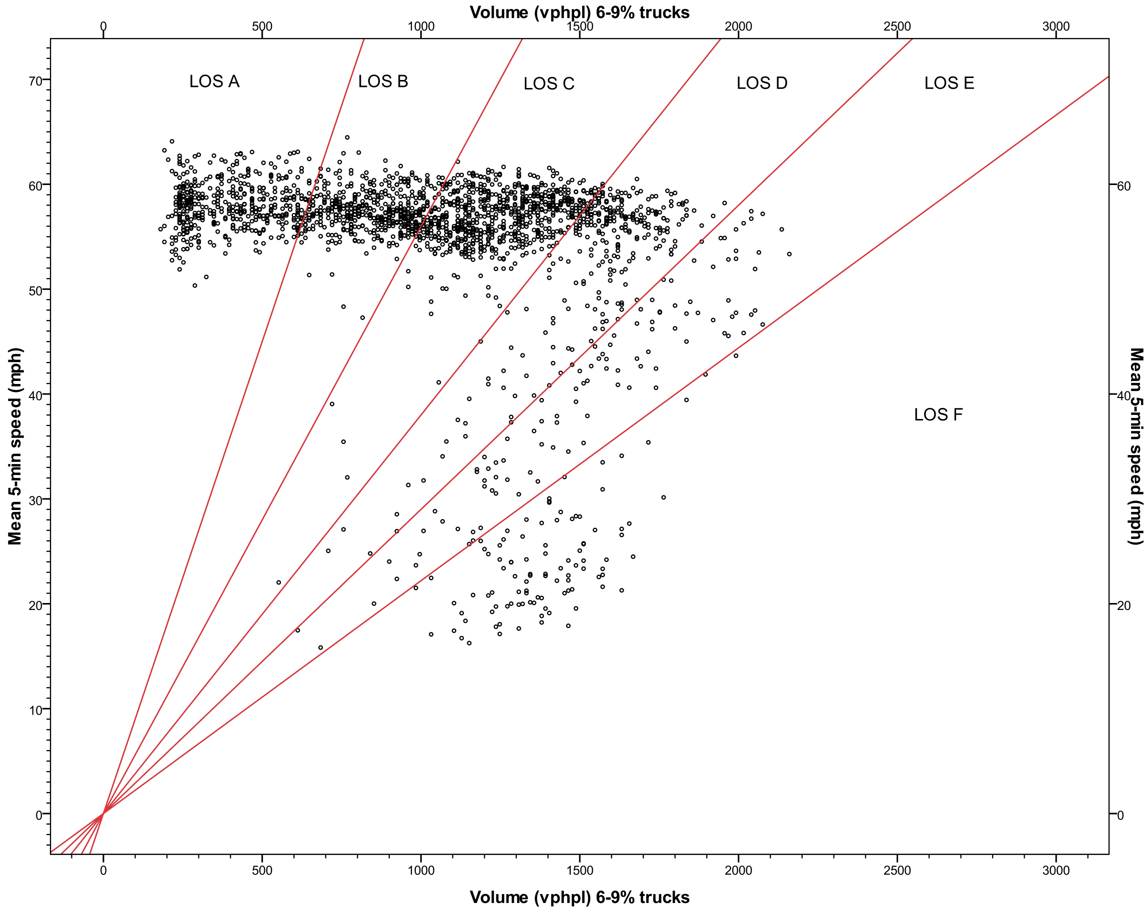

FIGURE 5.13 Speed-volume and LOS relationships- 6-9% trucks.

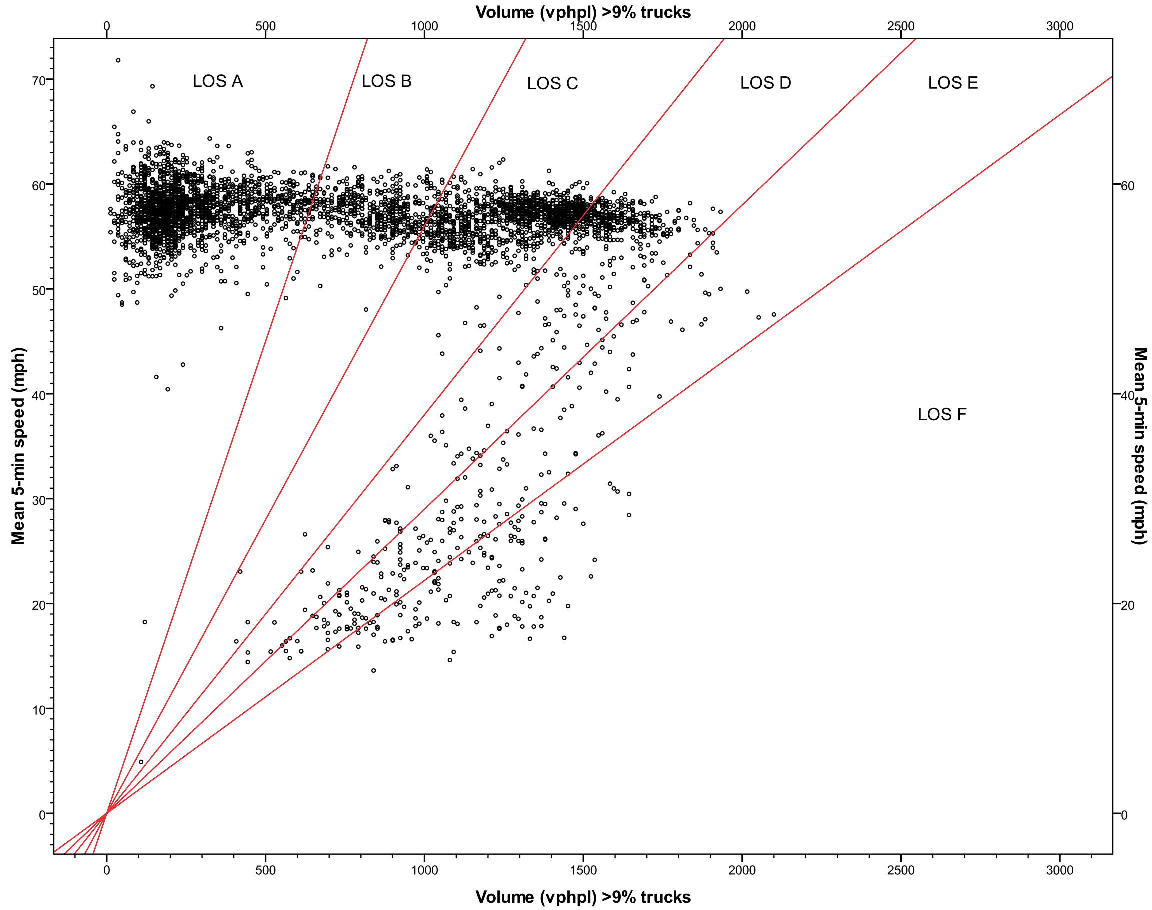

FIGURE 5.14 Speed-volume and LOS relationships- more than 9% trucks.

A PCE factor for PC is included in Table 5.10. It was calculated by dividing the average PC-PC headway when volume was greater than or equal to 2,000 vphpl, by the minimum PC headway in a PC-only traffic stream. This factor was meant to provide a direct comparison with the “ideal” minimum headway.

Table 5.10 indicates that HV presence in the traffic stream had a significant influence on PC as well as HV headways. Headways typically increased with increasing HV presence and thus the PCE factors also increased in parallel.

The HCM 2000 recommends a PCE = 1.50 for level basic freeway segments such as the study location. This value agreed with field data when truck presence did not exceed 3%, however higher PCE values were identified at higher truck presence levels. There are indications that vehicles in the heaviest analyzed class 9 may have a PCE value of 2.00 or higher, however not enough data were available in the study database for definitive conclusions.

Figures 5.15 and 5.16 provide a graphical representation of the relationship between PCE and heavy truck presence in the traffic stream for HV collectively (vehicle classes 4 and above) and PC, respectively.

Thus, based on the available information, the previously stated finding of lower PCE factors with a higher percentage of HV was not supported.

TABLE 5.10 Passenger Car Equivalent factor relation with heavy vehicle percentage in the traffic stream.

	Passenger car		Truck class 8		Truck class 9		Vehicle class 4 and above	
Heavy vehicle percentage	Headway (seconds)	PCE	Headway (seconds)	PCE	Headway (seconds)	PCE	Headway (seconds)	PCE
>0-3%	1.60	1.12	2.14	1.50	2.21	1.55	2.14	1.50
3-6%	1.68	1.17	2.08	1.45	2.83	1.98	2.32	1.62
6-9%	1.73	1.21	2.52	1.77	2.48	1.74	2.48	1.74
>9%	1.69	1.18	2.54	1.77	3.26	2.28	2.51	1.76

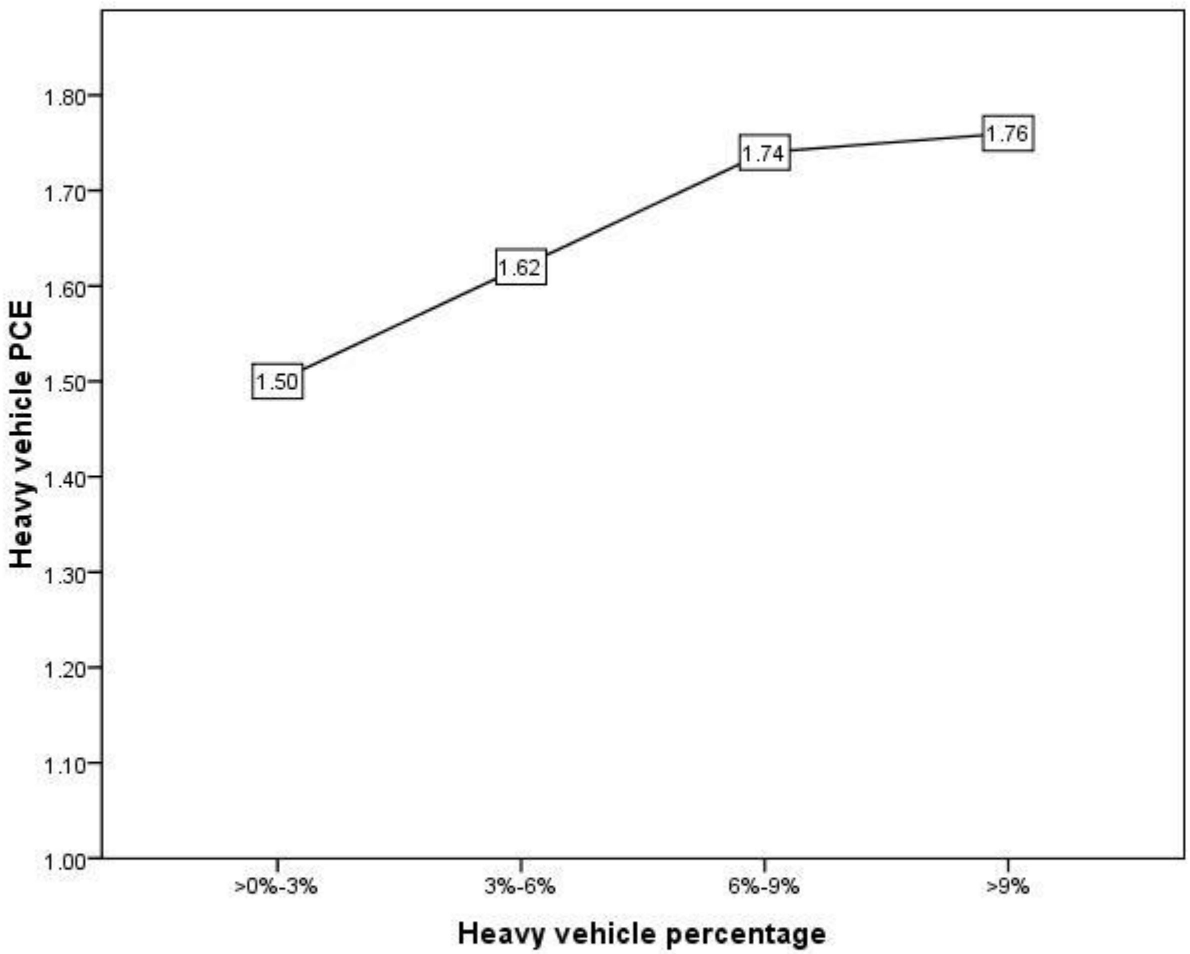

FIGURE 5.15 Heavy Vehicle PCE vs. Heavy Vehicle percentage in the traffic stream.

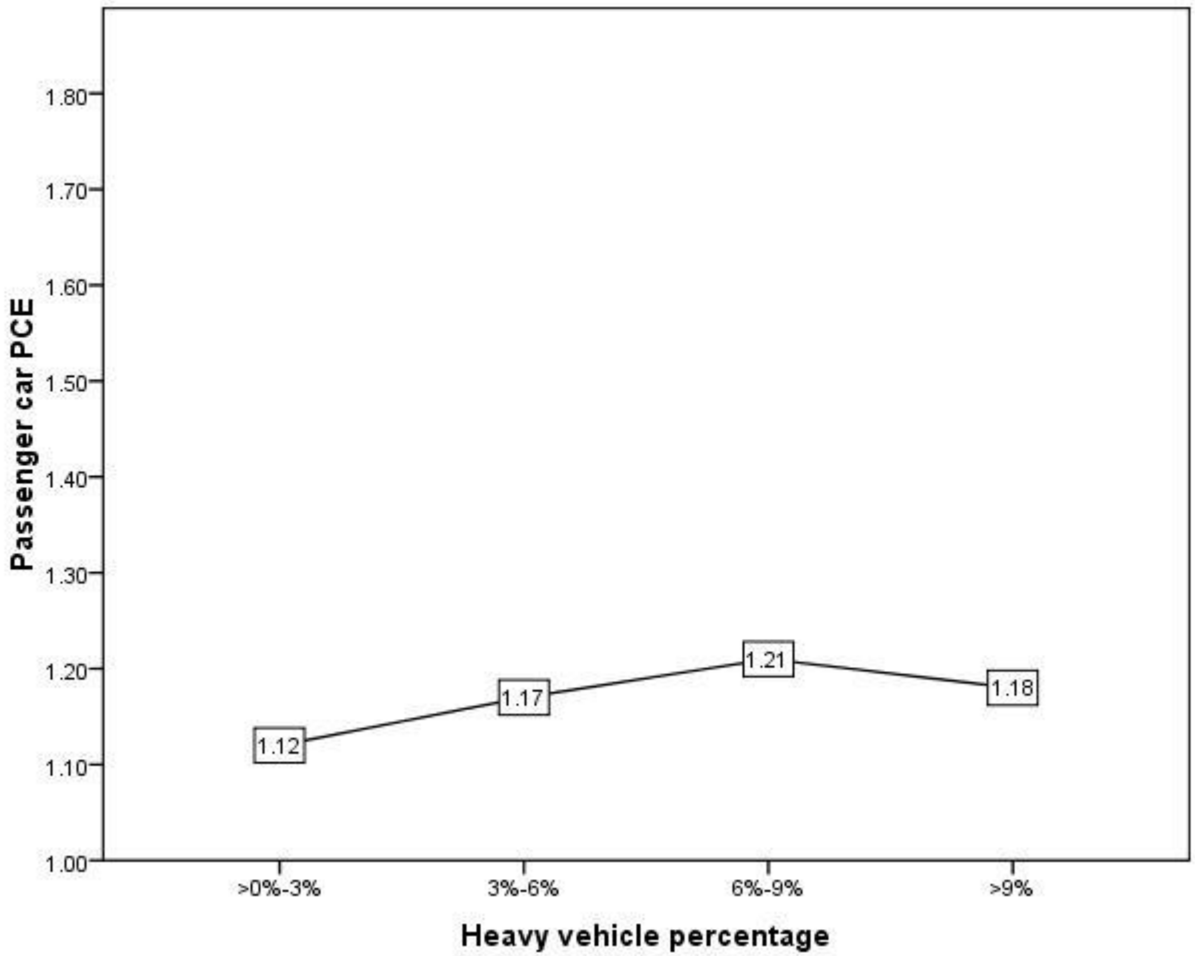

FIGURE 5.16 Passenger Car PCE vs. Heavy Vehicle percentage in the traffic stream.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of the thesis was to identify Heavy Vehicle (HV) characteristics that have an impact on freeway throughput at various congestion levels with an emphasis on operations at LOS E and F. Furthermore, it was desired to use the available database in order to derive Passenger Car Equivalent (PCE) factors obtained under congested and severely congested conditions in order to compare them to the HCM 2000-recommended PCE factors that were calibrated under 'steady-flow' conditions.

Since PCE factors are based on the ratio of Heavy Vehicle to Passenger Car (PC) headway ratio per equation ***2.1*** below, the present research effort focused on factors affecting HV and PC headways at various congestion levels.

$$\text{PCE}=\frac{h_t}{h_c} \quad \textbf{2.1}$$

Headway relation with speed

A fundamental Headway-Speed quadratic equation (see equation ***5.1*** below) was fit to the available data and calibrated at the aggregate analysis level, for average headways across all analyzed vehicle classes. A high correlation between the dependent and the independent variables was identified (r = 0.981); the model had a very good fit at the 0.000 significance level.

$$Vehicle\ Headway = 0.0018 * Speed^2 + (-0.14) * Speed + 4.94 \quad \textbf{5.1}$$

Where, Vehicle Headway was measured in seconds.
Vehicle Speed (mid-point of speed range) was measured in mph.

Minimum headways (operation at capacity) were associated with speeds ranging between 40 and 45 mph and densities slightly higher than 45 veh/mi (LOS F), as shown in Figure 5.3.

Recognizing the overarching relationship between headways and speed, the remainder of the data analysis focused on identifying additional factors affecting HV and PC headways and especially factors that may have a differential effect on these two types of headways.

Lagging Passenger Car Headways

Researchers had previously established that PC drivers maintained longer headways when following HV than when following lighter vehicles. Two types of 'light vehicles', PC and light trucks (vehicle classes 2 and 3 respectively-see Figure 3.1 for definitions) and two types of 'HV' (vehicle classes 8 and 9) were used to verify whether this finding applied to the study database. An additional dimension in this investigation was a separate analysis for each of nine 5-mph speed ranges. It was indeed verified that for each analyzed speed range the headways PC drivers maintained from 'light vehicles' were statistically indistinguishable; the headways they maintained from class 9 vehicles were statistically significantly longer (Tables 5.6 and 5.7 and Figure 5.5). Although, their headways from class 8 vehicles were longer that those they kept from 'lighter vehicles' they were not always statistically significantly longer.

A clear pattern of PC drivers maintaining shorter headways from vehicles class 9 as speeds increased from 10-15 mph to 45-50 mph was evident.

Passenger Car-Heavy Vehicle Pair Headways

Contradictory findings about whether the headways PC maintained from HV were longer or shorter than those maintained by HV drivers following PC were addressed using separate headway comparisons with vehicle classes 8 and 9. PC drivers were found to maintain statistically significant shorter headways when following HV than the headways maintained by HV drivers following PC. This finding was valid both for class 8 and class 9 HV and for all analyzed vehicle speed ranges (Table 5.8 and Figures 5.6 and 5.7).

Gross Vehicle Weight-Headway Relation

Headway relations with a general Gross Vehicle Weight (GVW) classification indicated statistically significant larger headways maintained by vehicles with a GVW exceeding 30 kips compared to those with a GVW up to 15 kips (Table 5.9 and Figure 5.8) for all analyzed speed ranges (0 to >50 mph).

Heavy Vehicle Percentage and Passenger Car Equivalent Factor Relationship

Five-minute traffic flow summary information was used to identify PC-only periods and the minimum headway during these periods, corresponding to the facility capacity. This headway was compared to PC headways in mixed traffic at four levels of truck presence (>0-3%, 3-6%, 6-9% and >9% trucks in the traffic stream). PC and HV headways (identified separately for vehicles class 8 and 9; also for all vehicles classes 4 and higher) were found to increase with truck presence in the traffic stream (Table 5.10). A similar pattern was found for the

PCE factor, which was shown to be higher than the recommended HCM 2000 value of 1.5 for similar level, basic freeway segments (Table 5.10 and Figures 5.15 and 5.16). This finding did not agree with the currently accepted findings that the PCE factor decreases at higher HV presence levels.

The HV PCE value under congested conditions and with more than 9% HV presence was found to be 1.76 which is higher than the HCM-recommended HV PCE value of 1.5 under steady-flow conditions. Also, Passenger Cars were found to have the effect of more than 1 PC under congested conditions and a high HV presence.

6.2 Recommendations for future research

- The lack of adequate HV data operating under severely congested conditions in the analyzed database leads to a recommendation to identify a data collection site experiencing severely congested conditions for many hours each day, used by a significant number of HV so adequate sample sizes will be available to arrive at definitive conclusions and allow the inclusion of the 0-10 mph speed range in the analysis.
- It would be desirable that future data collection locations include a vehicle weight collection capability in addition to a vehicle classification capability. It is reasonable to assume, and there are indications in that direction in the analyzed data, that heavy vehicle drivers base their headway choice on vehicle weight. The GVW-headway relation analysis provided indications that vehicle class-based analyses may not adequately account for the overall vehicle weight (GVW) probably due to the payload effect. For

vehicle classes 3-6 maximum payloads can be 50% to 100% of the empty vehicle weight; for semi trucks classes 8 and 9 maximum payload may be up to 200% of their empty weight. Thus a fully loaded class 8 vehicle may be heavier than a half-empty class 9 vehicle; furthermore, empty and loaded vehicles in the same class may maintain substantially different headways, especially at lower speeds.

- It would be desirable to analyze vehicle spacing in order to identify vehicle spacing relations with speed, GVW and other parameters. This information will be useful in calibrating separate car-following mathematical models for each vehicle class that would be readily available as inputs for simulation packages.
- The present effort analyzed headways measured from front axle-to-front axle. Although this analysis is useful from a freeway capacity analysis point of view, headway and spacing between the rear bumper of a leading vehicle and the front bumper of a trailing vehicle would make more sense from the driver headway/spacing choice point of view.
- Future research can analyze the effect of three consecutive heavy vehicles in a lane forming a heavy vehicle "train" in order to test a finding of shorter headways between vehicles forming such "trains."
- It would be desirable to analyze the effect of heavy vehicle weight/power ratio on headways with field-collected data. Most of currently available information is based on simulated, non-calibrated runs.

BIBLIOGRAPHY

1. American Association of State Highway and Transportation Officials. (2004). *A Policy on Geometric Design of Highways and Streets, 2004*. American Association of State Highway and Transportation Officials, Washington, DC., 2004.

2. *Highway Capacity Manual 2000.* TRB, National Research Council, Washington, DC., 2000.

3. Roess, R., and Messer, C. Passenger Car Equivalents for Uninterrupted Flow: Revision of Circular 212 Values. In *Transportation Research Record 971.* TRB, National Research Council, Washington, DC., 1984, pp. 7-13.

4. Krammes, R., and Crowley, K. Passenger Car Equivalents for Trucks on Level Freway Segments. In *Transportation Research Record 1091.* TRB, National Research Council, Washington, DC., 1986, pp. 10-17.

5. West, J., and Thurgood, G. Developing Passenger-Car Equivalents for Left-Turning Trucks at Compressed Diamond Interchanges. In *Transportation Research Record 1484.* TRB, National Research Council, Washington, DC., 1995, pp. 90-97.

6. Webster, N, and Elefteriadou, L. A Simulation Study of Truck Passenger Car Equivalents (PCE) on Basic Freeway Sections. In *Transportation Research*, Vol. 33B, 1999, pp. 323-336.

7. Al-Kaisy, A., Hall, F., and Reisman, E. Developing Passenger Car Equivalents for Heavy Vehicles on Freeways During Queue Discharge Flow. In *Transportation Research*, Vol. 36A, 2002, pp. 725-742.

8. Seguin, E., Crowley, K., and Zweig, W. *Urban Freeway Truck Characteristics*, Vol. I: *Passenger Car Equivalents.* Report FHWA/RD-81/156. Institute for Research, State College, Pa., 1981.

9. Sarvi, M. Freeway Operation Characteristics of Heavy Commercial Vehicle Traffic. Presented at 88th Annual Meeting of the Transportation Research Board, Washington, DC., 2009.

10. Tanaboriboon, Y., and Aryal, R. Effect of Vehicle Size on Highway Capacity in Thailand. In *Journal of Transportation Engineering*, Vol. 116, No. 5. ASCE, 1990, pp. 658-666.

11. Rakha, H., Ingle, A., Hancock, K., and Al-Kaisy, A. Estimating Truck Equivalencies for Freeway Sections. In *Transportation Research record 2027.* TRB, National Research Council, Washington, DC., 2007, pp. 73-84.