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Heavy Vehicle Performance During Recovery From Forced-Flow Urban Freeway Conditions Due To Incidents, Work Zones and Recurring Congestion

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Heavy Vehicle Performance During Recovery From Forced-Flow Urban Freeway Conditions Due To Incidents, Work Zones and Recurring Congestion

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16. Abstract

Information contained in the Highway Capacity Manual on the influence heavy vehicles have on freeway traffic operations has been based on few field data collection efforts and relied mostly on traffic simulation efforts. In the 2010 Manual heavy vehicle impact is evaluated based on "passenger car equivalent" values for buses/trucks and recreational vehicles. These values were calibrated for relatively uncongested freeway conditions (levels of service A through C) since inadequate field data on heavy vehicle behavior under congested conditions were available. Field-collected headway information was based on the average headway for vehicles in a particular class, regardless of the type of vehicle they were following.

The goal of the present effort was to collect and analyze freeway field data on headways with an emphasis on heavy vehicle behavior under lower speeds typically associated with a level of service E (capacity) or F (forced-flow conditions). Contrary to previous efforts incorporated in the Highway Capacity Manual methodology, that disregarded the effect a leading vehicle has on headways, headway information was collected for ten leading/following vehicle pair types containing at least one passenger car (for example buses followed by passenger cars). Headway statistics were analyzed for nine speed ranges (up to 20 mph; 20-25 mph; 25-30 mph; 30-35 mph; 35-40 mph; 40-45 mph; 45-50 mph; 50-55 mph; and 55+ mph) and ten vehicle pair types. Passenger car equivalent values were derived for each speed range based on the average headway for a specific vehicle pair type divided by the average headway between passenger cars. A total of 3,981,810 individual vehicle records were used to construct the 2,645,210 vehicle pair records for which headway statistics were compiled. All analyzed information originated from the Milwaukee County, Wisconsin urban freeway system. Leading and following vehicle class and speed were found to significantly influence headways and passenger car equivalent values.

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Heavy vehicle, PCE, urban freeway, forced-flow.

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ACRONYMS USED IN THE REPORT

E_R = passenger-car equivalent for recreational vehicles

E_T = passenger-car equivalent for trucks and buses

FHWA = Federal Highway Administration

HCM = Highway Capacity Manual

HV = Heavy Vehicle

lb/hp ratio = Weight-to-Horsepower Ratio

LOS = Level Of Service

MOE = Measures Of Effectiveness

PC = Passenger Car

PCE = Passenger Car Equivalent

QDF = Queue Discharge Flow

RV = Recreational Vehicle

SPUI = Single-Point Urban Interchange

v/c ratio = Volume-to-Capacity Ratio

UNITS

1 m = one meter = 3.281 ft

h = headway (seconds)

lb/hp = pounds per horsepower

pc/mi/lane = passenger cars per mile per lane

pcphpl = passenger cars per hour per lane

vph = vehicles per hour

vphpl = vehicles per hour per lane

DEFINITIONS[1]

Distance gap: the distance between the rear bumper of a leading vehicle and the front bumper of a following vehicle.

Headway - The time between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles (for example, the front axle or the front bumper).[2]

Lead/lag vehicle pair: A vehicle pair comprising a leading vehicle (Lead) followed by another vehicle (Lagging vehicle-Lag vehicle) in the traffic stream. Such a pair is identified by a numeric code, for example vehicle pair type code 502 indicates a leading vehicle class 5 followed by a vehicle class 2 (see **Figure A1** for vehicle class codes and **Vehicle class** entry below).

Lost time: the time, in seconds during which an intersection is not used effectively by any movement; it is the sum of clearance lost time and start-up lost time.

Passenger-Car Equivalent - The number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under specified roadway, traffic, and control conditions.

Per-vehicle: vehicle classification count recording individual vehicle data such as speed, vehicle class and wheel base information

Queue Discharge Flow: a flow with high density and low speed, in which queued vehicles start to disperse.

Saturation flow rate: the equivalent hourly rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions, assuming that he green signal is available at all times and no lost times are experienced, in vehicles per hour per lane (vphpl).

Saturation headway: The average headway between vehicles occurring after the fourth vehicle in the queue and continuing until the last vehicle in the initial queue clears the intersection.

Start-up lost time: the additional time, in seconds, consumed by the first few vehicles in a queue at a signalized intersection above and beyond the saturation headway.

---

[1] From the 2010 Highway Capacity Manual.
[2] Front-axle-to-front-axle was used here.

DEFINITIONS (Continued)

Vehicle class: the Federal Highway Administration (FHWA) 13-category scheme of vehicle classification was used throughout the report. A visual representation of vehicles in each class is provided in **Figure A1**. Vehicle class definitions used in the report are provided below:

Vehicle class 1: Motorcycles
Vehicle class 2: Passenger cars
Vehicle class 3: Pick-ups/vans
Vehicle class 4: Buses
Vehicle class 5: Two-axle single-unit trucks
Vehicle class 6: Three-axle single-unit trucks
Vehicle class 7: Four or more single-unit trucks
Vehicle class 8: Small semi-truck
Vehicle class 9: Large semi-truck
Vehicle classes 10-13 were not included in the analysis.

Vehicle pair types: vehicle pairs defined based on the 13-category FHWA vehicle classification scheme shown in **Figure A1**. A three-digit convention is used herein, where the first digit signifies the vehicle class of the leading vehicle and the last digit signifies the vehicle class of the following vehicle. For example, **code 208** indicates passenger car followed by a small semi-truck and **code 802** indicates a small semi-truck followed by a passenger car.

Vehicle type: a group of vehicle classes considered as one vehicle type for the purpose of analyzing vehicles with similar vehicle performance characteristics.

EXECUTIVE SUMMARY

Information contained in the Highway Capacity Manual on the influence heavy vehicles have on freeway traffic operations has been based on few field data collection efforts and relied mostly on traffic simulation efforts. In the 2010 Manual heavy vehicle impact is evaluated based on "passenger car equivalent" values for buses/trucks and recreational vehicles. These values were calibrated for relatively uncongested freeway conditions (levels of service A through C) since inadequate field data on heavy vehicle behavior under congested conditions were available. Field-collected headway information was based on the average headway for vehicles in a particular class, regardless of the type of vehicle they were following.

The goal of the present effort was to collect and analyze freeway field data on headways with an emphasis on heavy vehicle behavior under lower speeds typically associated with a level of service E (capacity) or F (forced-flow conditions). Contrary to previous efforts incorporated in the Highway Capacity Manual methodology, that disregarded the effect a leading vehicle has on headways, headway information was collected for ten leading/following vehicle pair types containing at least one passenger car (for example buses followed by passenger cars). Headway statistics were analyzed for nine speed ranges (up to 20 mph; 20-25 mph; 25-30 mph; 30-35 mph; 35-40 mph; 40-45 mph; 45-50 mph; 50-55 mph; and 55+ mph) and ten vehicle pair types.

Passenger car equivalent values were derived for each speed range based on the average headway for a specific vehicle pair type divided by the average headway between passenger cars. A total of 3,981,810 individual vehicle records were used to construct the 2,645,210 vehicle pair records for which headway statistics were compiled. All analyzed information originated from the Milwaukee County, Wisconsin urban freeway system. Leading and following vehicle class and speed were found to significantly influence headways and passenger car equivalent values.

The headway analysis in the present effort was based on statistics collected for ten lead/lag (leading/following) vehicle pair types for speeds up to 65 mph. This in-depth view of headway driver behavior allows a more accurate representation of the speed-volume-traffic density relationships, which extends into congested conditions, which were not addressed in any depth in the current (2010) Highway Capacity Manual. Estimates of the prevalence of each lead/lag vehicle pair type can be used in analyzing freeway operations for planning purposes; use of exact counts from vehicle classification stations would be recommended for use in freeway operations analyses of existing freeway facilities in order to develop facility-specific speed-volume-traffic density relationships reflecting existing traffic composition.

Findings in the present effort are especially useful in micro-simulation efforts. Headway information for particular leading/following vehicle pair types at each speed range can be used to calibrate car-following models to accurately represent real-world traffic conditions. The findings, for example, which passenger car drivers keep long distances when following larger vehicles, or that small semi-trucks (vehicle class 8) keep headways very similar to those observed between passenger cars, may be overlooked in a pure dynamic simulation model.

Dynamic heavy vehicle performance-based headway simulation values can benefit from cross-checking against field-based information provided herein.

Whether the professional's interest is in planning or operations freeway analyses, or freeway simulations, it is recommended that present effort headway and/or passenger car equivalent findings be used, since they address headway information under congested traffic conditions, an area in which the Highway Capacity Manual does not currently provide detailed guidance.

Headway and passenger car equivalent values derived through the present effort are suitable for addressing conditions at many urban freeways currently operating at capacity or even at Level of Service F. Freeway construction zones often result in similar conditions due to lane closures or general construction-related activities; Departments of Transportation can benefit from the present effort in establishing work zone transportation management plans.

The present report provides passenger car equivalent values based on headway ratios. Findings can be converted to other potential passenger car equivalent definitions, for example, if a traffic density-based passenger car equivalent relationship is desired, the relationship between traffic density, volume and speed can be used to achieve this goal.

INTRODUCTION

Information contained in the Highway Capacity Manual on the influence heavy vehicles have on freeway traffic operations has been based on few field data collection efforts and relied mostly on traffic simulation efforts. In the 2010 Manual heavy vehicle impact is evaluated based on "passenger car equivalent" values for buses, recreational vehicles and trucks. These values were calibrated for relatively uncongested freeway conditions (levels of service A through C) since inadequate field data on heavy vehicle behavior under congested conditions were available.

A number of field data collection efforts, that were not included in deriving the passenger car equivalent values used in the Highway Capacity Manual, indicated that heavy vehicle impacts on traffic operations may increase as freeway congestion levels increase and freeways operate under unstable flow conditions.

The goal of the present effort was to collect and analyze field data with an emphasis on heavy vehicle behavior under lower speeds and derive passenger car equivalent values under such conditions.

REPORT ORGANIZATION

The body of the report is organized into sections addressing the **Literature Review**, followed by a summary of **Study Objectives**, a **Database Description** and information about the **Data Collection Objectives**. The **Data Collection Methodology**, **Data Reliability Checks** and **Data Analysis** description sections follow. The final sections include **Findings**, **Conclusions**, and **Recommendations**.

Detailed information supplementing these sections is provided in **Appendices A through C**. **Appendix A** provides supplemental information related to the study database; **Appendix B** provides the definitions of analyzed leading/following (lead/lag) vehicle pair types and statistical test results on headway differences between those vehicle pair types. **Appendix C** provides central tendency headway statistics and calculated passenger car equivalent values relations with speed for the analyzed vehicle pair types.

References to page numbers **Tables** and **Figures** are in **bold** type. Letters preceding a page number, Table or Figure number indicate materials presented in the corresponding Appendix; for example **Table C10** will be found in **Appendix C**.

A list of **Acronyms, Units** and **Definitions** is included in the front matter of the report.

LITERATURE REVIEW

Introduction

Heavy vehicles (HV) with their larger dimensions, lower acceleration rates and need for longer stopping distances adversely affect freeway traffic operations. The adverse impact of HV on freeway operations has been noted since the first Highway Capacity Manual (HCM) edition in 1950. A variety of methods to account for the presence of HV in freeway traffic have been used in subsequent HCM editions and various research efforts *(1)*. Most proposed methods define a "base" traffic flow condition based on a traffic stream where only passenger cars (PC) are present and a "comparison," "equally performing" condition where one or more types of HV are present in the traffic stream. Once the two conditions have been established, the impact of HV is evaluated by calculating a specific multiple of PC that each HV is "equivalent" to in the comparison traffic stream. Starting with the 1965 HCM, the term used for this multiple was "passenger car equivalent" (PCE). The following passages from the 1965 HCM provide the motivation for and a definition of PCE *(2)*:

> "Trucks (defined for capacity purposes as cargo-carrying vehicles with dual tires on one or more axles) reduce the capacity of a highway in terms of total vehicles carried per hour. In effect, each truck displaces several passenger cars in the flow. The number of passenger cars that each dual-tired vehicle represents under specific conditions is termed the 'passenger car equivalent' for those conditions."
>
> PCE is: "The number of passenger cars displaced in the traffic flow by a truck or bus, under the prevailing roadway and traffic conditions." *(2)*

One of the motivations for research efforts to refine PCE factors was a Federal Highway Administration (FHWA) effort to update the national highway cost allocation study *(1)*. Part of this effort, already in progress before the 1985 HCM edition, was to establish methods to quantify the percentage of highway capacity consumed by various classes of vehicles. PCE values were being established for urban arterials, urban freeways, rural two-lane two-way roadways and rural freeways *(3)*.

The need to update existing PCE values was based on the significant changes in new HV dimensions, weights and engine performance that had an effect on costs due to their impact on traffic operations. HV effects were most noticeable on grades, thus the weight/horsepower ratio was included in studies in order to account for the effect of grades. The focus on HV cost effects motivated studies where PCE values focused on the detrimental speed effect HV presence had on comparison traffic stream speeds. Speed differentials due to the presence of HV could be directly converted to delay and thus to a monetary value.

Efforts to determine PCE values for traffic operations applications were based on a wider variety of metrics, described in later sections.

PCE factor history

In the first HCM edition (1950 HCM) *(4)* a HV was considered to be equivalent to two PC when operating on multilane, level highways. This equivalency remained unchanged in the 1965 HCM *(2)*, where the term "passenger car equivalent" first appeared. Equivalents for trucks in the 1965 HCM were based on the delay to PC caused by HV *(5)*. PCE values applied to freeway operations were related to the level of service (LOS), defined in terms of operating speed and v/c ratio *(6)*. PCE for LOS ranges A through C were assigned different values than PCE for LOS D and E.

In the interim, between the 1965 and the 1985 HCM publications, no uniform definition of the meaning of the term PCE existed, and the intended use of PCE values varied between highway cost allocation and traffic operations studies. Different methodologies were applied for two-lane highway, multilane highway and interrupted flow facility evaluations; no methodology uniformity existed within each evaluation type. Proposals for a change in the freeway LOS definition were put forth by a number of authors who favored use average running speed and/or density *(7, 8)*. At the same time, simulation was used to establish PCE for Circular 212 *(8)* that served as the basis for the 1985 HCM *(9)* values.

Ideas started to crystallize about using density as the basis for PCE value derivation *(10)*. Some authors voiced opinions that PCE values are independent of traffic flow for a given grade, that there is no definitive evidence for a flow-PCE relationship, or that a simple linear relationship between the two variables should be replaced by a multi-variate model *(1, 5, 11)*. Further study based on field data was suggested to address the issue. Arguments on this topic were based on relatively low flow rates, where a PCE-traffic flow relationship may have been very weak due to the wide headway variability under low flow conditions.

Most efforts to establish PCE in the period following the 1965 HCM publication *(2)* were focused on two- or multi-lane highways *(12-19)*. A few focused on freeways but were rather limited in the extent of analyzed sites *(20-22)*. A study using eleven freeway sites across four urban areas in the U.S. was focused on cost allocation for HV rather than traffic operations/capacity analysis *(23)*.

Use of a lower PCE than the 1965 HCM value was proposed *(5)* based on a research study *(23)* that concluded that a PCE value of 2.0 applied only to semi-trucks under the highest analyzed volume conditions; single-unit truck PCE of 1.5 and 1.6 were suggested, depending on the number of axles.

Roess and Messer, co-editors of the 1985 HCM, identified the discrepancies between efforts to establish PCE. They decided that three comparison methods between "base" and mixed traffic streams were more relevant to defining the effect of HV on traffic operations: comparing traffic streams with equal v/c ratios, equal densities or equal spatial headways *(5, 9)*. The 1985 HCM *(9)* PCE adopted the spatial headway approach used in the Institute for Research Study *(23)*. LOS was defined in terms of density and average running speed, with a PCE for level terrain of 1.7. Separate PCE values were provided for three groups of weight-to-horsepower HV; PCE values were no longer dependent on LOS *(6)*.

Around the time of the 1985 HCM publication, investigators recognized that the adverse effect of heavy vehicles was due to their larger sizes (they took more freeway space), inferior acceleration and deceleration capabilities (large gaps formed in front of HV) and the impact their presence had on drivers of smaller vehicles (who typically kept longer distances from HV being concerned with aerodynamic disturbances, splash and spray, sign blockage, offtracking, underride hazard, etc. *(10, 24)*). Thus, some researchers focused on analyzing the interactions of particular leading-following pairs of vehicle types (for example PC following PC, or PC following HV).

In the HCM 2000 *(25)* and the 2010 HCM *(26)* PCE values were defined based on vehicle type alone (trucks/buses and recreational vehicles) and remained unchanged between these two editions. The values were calibrated for a traffic density of 20 pc/mi/lane (LOS C) using a typical truck/bus with a weight-to-power ratio of 164 lb/hp. Vehicle type, grade length/steepness and percent heavy vehicles affected PCE values.

The following bullets provide a summary of the PCE term evolution (the term first appeared in the 1965 HCM *(2)*):

- 1950 HCM: On multilane highways in level terrain trucks have the same effect as two passenger cars *(4)*.
- 1965 HCM: PCE is the number of passenger cars displaced by a truck or bus under prevailing traffic conditions *(2)*.
- 1985 HCM: PCE is the number of passenger cars that would consume the same percent of the freeway's capacity as one truck, bus or recreational vehicle (RV) under prevailing roadway and traffic conditions *(9)*. Average speed was used as the criterion to establish PCE.
- 1997 and 2000 HCM*(25, 27)*: PCE is the number of passenger cars displaced by a single heavy vehicle of a particular type under specified roadway, traffic and control conditions *(25)*. Average traffic density was used as the criterion for equivalent traffic streams.
- 2010 HCM*(26)*: "PCE is the number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under specified roadway, traffic, and control conditions."

Field data-based efforts

Historically, the development of freeway PCE factors was based on limited field data and extensive use of simulation *(1, 10, 14, 15, 19, 28, 29)*. Field data would be ideal in order to develop accurate and reliable PCE factors. The problem was that a large number of data collection sites and a very large vehicle classification database would be necessary in order to address all possible combinations of factors that had been identified to significantly affect PCE values (traffic volumes, percent trucks, grade length and steepness, vehicle performance, vehicle type mix, etc.), making the creation of a sufficient field database impractical. Thus, simulation-based results were used extensively in developing the HCM PCE values that professionals use in everyday applications.

Early field databases used in developing HCM freeway PCE values were based on a limited number of data collection sites; furthermore, PCE values were based on traffic stream operations ranging from free-flow to mildly congested conditions. A number of studies identified a relationship between increasing congestion levels and higher PCE values, however very few data points were available for the highest flow levels associated with free-flow conditions.

One of the earliest documented freeway field data-based vehicle classification efforts *(30)* collected 287,000 individual vehicle observations on one basic freeway section, three merge areas one diverge and three weave areas, all on level terrain. Twelve separate vehicle types ranging from motorcycles to combination vehicles were identified. Despite the large database size, information on many vehicle classes, especially HV was not adequate for definitive conclusions, especially for volumes above 1,500 vphpl.

The 1985 HCM recreational vehicle (RV) PCE values were determined from field observations on Canadian highways *(15, 31)*.

An effort by Al-Kaisy et al. *(32)* used field data from two Canadian locations to determine PCE. It was one of the rare efforts based on field-collected data to examine PCE for traffic under congested conditions--queue discharge flow (QDF). Approximately 186 hours of observations were included in this analysis that classified vehicles with a length of less than 21 feet as autos with all other vehicles classified as HV.

A 2008 effort *(33)* collected 1.6 million individual vehicle field-collected data at three urban level basic freeway sections. Approximately 130,000 of these observations corresponded to oversaturated conditions. This information was used to develop PCE values for a number of vehicle classes.

HV mix and PCE

Efforts to quantify passenger car equivalents (PCE) for heavy vehicles (HV) varied in terms of the number of different types of HV they analyzed, as well as in the logic used in establishing specific PCE values for specific HV types. The following HV definition is extracted from the HCM 2010 *(26)*:

> "A heavy vehicle is defined as any vehicle with more than four wheels on the ground during normal operation. Such vehicles are generally categorized as trucks, buses, or RVs. Trucks cover a wide variety of vehicles, from single-unit trucks with double rear tires to triple-unit tractor-trailer combinations. Small panel or pickup trucks with only four wheels are, however, classified as passenger cars. Buses include intercity buses, public transit buses, and school buses. Because buses are in many ways similar to single-unit trucks, both types of vehicles are considered in one category. RVs include a wide variety of vehicles from self-contained motor homes to cars and small trucks with trailers (for boats, all-terrain vehicles, or other conveyances). It should be noted that most sport-utility vehicles have only four wheels and are thus categorized as passenger cars."

Establishment of realistic PCE values requires a balance between the competing goals of accurately representing the impact of HV on traffic operations without unnecessarily complicating the data collection and calculations involved in this effort.

A number of research efforts concentrated on defining PCE values for all HV types collectively *(1, 22, 34)*. However, the observation that one PCE factor does not reflect the diverse HV population in the traffic stream was the motivation for efforts that considered two or more HV types *(28, 29, 35)*. Methods to produce a composite PCE value were proposed.

An extensive field data-gathering effort *(30)*, based on 287,000 individual vehicle observations classified in thirteen separate vehicle types determined that pickups, utility vehicles and vans were indistinguishable from passenger cars for PCE calculation purposes regardless of volume level. Single-Unit trucks and buses had similar PCE values, that were higher than those of the smaller vehicles and semi-trucks had the highest PCE values.

Differences between HV types were recognized in the 1985 HCM that included separate PCE for three groups of weight-to-horsepower HV; in the 2000 and 2010 HCM editions *(25, 26)* PCE values were defined based on two vehicle types (trucks/buses and recreational vehicles) with a truck weight-to-horsepower ratio of 164 lb/hp.

Individual vehicle (per-vehicle) classification counts at urban level basic freeway sections operating under a variety of traffic flow conditions were analyzed in a 2008 effort *(33)*. An analysis of vehicle performance based on the FHWA 13-vehicle class scheme (**Figure A1**) indicated that grouping vehicles in three categories would be adequate and practical in representing differences between vehicles in the traffic mix. Vehicles were aggregated into the passenger car (classes 2 and 3), light truck (classes 4-7) and heavy truck (classes 8-13) groups. This grouping was based on average headway characteristics.

Headway, spacing, vehicle class and PCE

A few research efforts analyzed per-vehicle field-collected classification data that allowed the calculation of headway and spacing between individual pairs of vehicles whose vehicle class, speed and other information was recorded. Given the focus of the present effort on collecting per-vehicle information, this section focuses on the findings of such efforts. An early significant effort, described in the next paragraph, collected headway information about a vehicle belonging to a specific vehicle class without being concerned about the class of the vehicle leading the subject vehicle. Later significant efforts recognized that headways were related not only to vehicle class, but also to the vehicle class of the leading vehicle.

Vehicle classification data on 287,000 individual vehicles were analyzed *(30)* to develop PCE values based on the headway ratios shown in the formula below. This effort was based on average observed headways for twelve vehicle classes, regardless of what type of vehicle was leading the one for which information was collected. For a given set of physical traffic and environmental conditions j, the denominator on the right-hand-side is the observed headway for passenger cars; the numerator is the observed headway for vehicle type i. Headway values were not reported; the ratio ranged from 0.5 for motorcycles under light flows to 2.0 for semi-trucks under heavier flows.

$$PCE_{i,j} = \frac{H_{i,j}}{H_{pc,j}} \qquad \textbf{(1)}$$

Where:
i is a specific vehicle type (for example a 3-axle truck)
j is a specific set of physical, traffic and environmental conditions
$\mathbf{H_{pc,j}}$ is the mean passenger car headway under traffic and environmental conditions j
$\mathbf{H_{i,j}}$ is the mean headway for vehicle type i under traffic and environmental conditions j

Data collected on an uninterrupted flow facility in Thailand *(34)* were used to develop PCE values when the facility was operating at capacity (LOS E). Data were summarized in five- and fifteen-minute periods. Vehicles were classified into three types: “small” (S = passenger cars), “medium” (M = four-wheeled vehicles larger than a passenger car) and “large” (L = all vehicles with more than four wheels). The average minimum headways for the nine combinations of leading-following vehicles were established and analyzed. It was determined that large vehicle drivers kept the longest headways when following any size vehicle. Intermediate headways were associated with middle-sized vehicles, and the shortest headways were maintained between pairs of passenger cars. Most of the headway differences between observed vehicle pairs were not, however, statistically significant. Pairs of vehicles that involved no large trucks kept statistically significantly shorter headways among themselves.

PCE values were calculated based on the following formula:

$$PCE = \{(1-p)(H_{L\text{-}S} + H_{S\text{-}L} - H_{S\text{-}S}) + p(H_{L\text{-}L})\}/H_{S\text{-}S} \qquad \textbf{(2)}$$

Where:

p is the proportion of large vehicles in the mixed traffic stream

$\mathbf{H_{X\text{-}Y}}$ is the average minimum headway between a leading vehicle type X and a trailing vehicle type Y where X, Y ∈ {S, M, L}

Similar, non-statistically significant differences observed in another study tended to become smaller with increasing **traffic volumes** *(36)*.

A study based on freeway sites in Tokyo, Japan and Melbourne, Australia *(37)* used cameras to track and analyze headways between 120 pairs of HV following PC and 120 pairs of PC following HV under congested conditions. The relative speeds and spacings of each vehicle pair were tracked over 700 m and recorded every 0.15 sec. The longest headways were observed for cars following trucks, intermediate headways were observed for trucks following cars and the shortest headways were for cars following cars. Headways were up to 10 sec for speeds of 2 mph and down to 2 sec for 37 mph.

A PCE definition based on the mean headways kept between combinations of leading-following vehicle pair types (limited to passenger cars (P) and "trucks" (T) vehicle types) was proposed *(10)*, using the following equation (its derivation is addressed in the PCE equations section):

$$PCE = \frac{\{(1 - P_T)\left(h_{M_{PT}} + h_{M_{TP}} - h_{M_{PP}}\right) + P_T h_{M_{TT}}\}}{h_{M_{PP}}} \qquad \textbf{(3)}$$

Where:

PCE passenger car equivalent value

$\boldsymbol{P_T}$ proportion of trucks in mixed traffic

$\boldsymbol{h_{X_{YZ}}}$ average headway in mixed traffic in sec:

X value: **M** mixed traffic; **B** base traffic

Y, Z values: **P** passenger car; **T** truck (***Y*** following vehicle; ***Z*** leading vehicle)

Congestion level

The focus herein is on heavy vehicle behavior under congested conditions. The majority of past PCE quantification efforts analyzed HV behavior under uncongested traffic conditions. Evidence that PCE values increased as traffic flow increased has been abundant, however, few studies addressed PCE values at LOS E, F or at queue discharge flow conditions.

Adverse HV effects on traffic flow have been mainly attributed to the following factors: larger vehicle dimensions that consume a larger proportion of the available space, lower acceleration rates that create longer gaps in front of HV, lower deceleration rates that require their drivers to maintain longer safety distances from leading vehicles and their effect on drivers of smaller vehicles following HV who generally tend to keep longer distances from large vehicles so their line of sight to traffic control devices is not limited, the risk of a rear-end collision/underride is reduced and enough space is available to accelerate, should they need to change lanes.

A concise presentation of the interaction between congestion level and HV properties is provided below *(38)*:

> "...Under all circumstances the amount of space occupied by a particular vehicle type is governed by its physical length and the distance gap to the next vehicle. In free-flow conditions, this distance gap is of several orders larger than the physical length of a vehicle, and the relative difference in the space occupied between different classes of vehicles is small. Under these conditions, and particularly in the case of a near-empty road, the effect of trucks on traffic operations is negligible. However, in denser traffic conditions, where lower mean speeds prevail, larger vehicles occupy relatively more space (vehicle length + distance gap) than do smaller vehicles. For example, at a complete standstill, an 18-m [59-ft] truck occupies the equivalent of approximately three passenger cars, whereas at a speed of 80 km/h [50 mph], the difference between the highway spaces occupied by these two vehicle classes is much smaller..."

Non-statistically significant differences in headway-based PCE values for three vehicle sizes (heavy vehicles, middle-sized vehicles and passenger cars) observed during peak hours tended to become smaller with increasing **traffic volumes** *(36)***.**

Three vehicle types (pickups, utility vehicles and vans) were found to have indistinguishable PCE values from passenger cars regardless of **volume level** based on field data collected in the presence of freeway speeds lower than 30 mph *(30)*. PCE values tended to increase with increasing **traffic volumes** (very little information was available for heavier vehicles at higher hourly volume levels-findings were tentative for those conditions). Similar results using PCE based on spatial headways on level grades were documented elsewhere *(36)*.

An analysis of headway data *(10)* collected at two six-lane basic freeway segments by a previous research effort *(23)* found that headways showed a very wide variation at low **traffic volumes** (400-1,300 vph), a result in agreement with previous findings *(39)* that headway mean and standard deviation were approximately equal under similar **traffic volumes**. The authors identified that PCE increased with increasing **traffic flow.** They cautioned, however, that only limited information was available at the lowest and highest analyzed flow rates, thus these values should not be considered precise. The average PCE values in this effort were in general agreement with other findings *(1, 2, 17, 23)*.

PCE values were developed based on a dynamic HV performance microscopic simulation study *(29)* for **flow rates** between 500 and 2,000 vphpl. PCE values were found to be sensitive to flow rate at level grades-they increased with increasing flow rates, especially at the higher flow rates investigated. Free-flow speeds (at low flow rates) were found not to influence PCE values to a significant degree.

A number of other authors recognized the effect of congestion on PCE values, as well *(25, 38, 40, 41)*. Studies on the effect of **speed** or **LOS** on PCE demonstrated a large variation in PCE values between free-flowing and congested conditions.

Field data collected under queue discharge conditions as vehicles were leaving freeway bottlenecks were analyzed *(32)*. Results were “generally consistent” with the hypothesis that PCE are higher under **oversaturated conditions** than **under-saturated conditions**—however, no statistical conclusions were provided for these findings.

An effort *(42)* to expand findings in the realm of congested freeway operations under queue discharge flow (QDF) used field data from a previous study *(32)* and produced microscopic simulation runs, calibrated on the field data for QDF. Simulation was used to investigate PCE values that would account for grade length and steepness as well as **percent trucks in the traffic stream** under congested conditions. Findings suggested that PCE values under QDF conditions were higher than those suggested by the HCM 2000 *(25)*.

A variety of congestion level proxies were used in research efforts to establish PCE values *(40)*: **Level of congestion** measured in a traffic density range between 15 and 40 pc/mi/ln was not fount to significantly affect PCE for grades up to 4%. **Delay comparison** –based PCE values were found to increase with increasing **traffic volume** *(43)*.

A 2008 study by Drakopoulos et al. *(33)* analyzed vehicle classification field data from three level basic freeway locations using the ratio of HV-to-PC headways ($PCE = \frac{h_{HV}}{h_{PC}}$). Separate values were calculated for uncongested and congested conditions. Uncongested conditions were assumed to be present when speeds were greater than 50 mph; three **congestion levels** were defined within the forced flow regime, based on vehicle speeds: 0-20 mph, 20 to 35 mph and 35-50 mph. PCE were found to increase as **speeds** decreased from uncongested to most-congested conditions.

PCE at signalized intersections

The effect of heavy vehicles at signalized intersections has been recognized in the HCM through the PCE-based heavy vehicle factor f_{HV}, applied on traffic volumes measured in the field as part of the calculation of the saturation flow rate. A number of studies focused specifically on the effect heavy vehicles have on vehicle headways at the beginning of the green phase (startup lost time), especially when they are located in the first few positions at the beginning of the queue.

The effect of heavy vehicles on traffic operations in freeways operating under breakdown conditions bears a lot of similarities to the effect HV have at signalized intersections since, under breakdown conditions, HV accelerate from a stop (or a very low speed) multiple times and other drivers are not able to change lanes in order to avoid slow-moving HV. Thus, findings based on signalized intersections can inform the analysis of oversaturated freeway conditions in terms of variables that significantly affect PCE and the methods used to calculate them.

Early work on developing PCE factors for signalized intersections focused on the time required to cross an intersection. **Vehicle size** was identified as a significant variable; separate PCE were developed for heavy and medium trucks-higher PCE values were computed for larger vehicles. It was noted that **passenger car drivers kept longer headways from leading larger vehicles** than they kept from leading passenger cars *(43-50)*. Similar findings were documented in a study that provided separate PCE for SUVs, vans and pickup trucks in a later study. Factors identified as affecting the calculated PCE included, **heavy vehicle percentage** (larger PCE values for higher percentage *(50-52)*, **traffic volume** (higher PCE values for higher flow *(52))*.

Signalized intersection PCEs were developed for various **types of HV** in 1984 as part of a cost allocation study *(53)*. Simulation was used to estimate the additional travel time to cross an intersection when HV were present in the traffic stream, compared to the travel time required for a PC-only traffic stream.

A 1995 study *(54)* focused on developing PCE at signalized single-point urban interchanges (SPUI) identified **truck length**, turning and **acceleration characteristics** and the **behavior of drivers following HV** as the most important parameters affecting PCE. The effect of a **truck in the lead position** at the stop line was discussed. Longer headways were observed due to lower truck acceleration rates; also due to passenger car drivers keeping longer distances from trucks. This result was found to result in delays for all queued vehicles. The cumulative effect of a truck in the first queue position was found to extend to the first seven passenger cars behind the truck *(49, 54)*.

Earlier work on developing PCE factors for signalized intersections was mostly motivated by efforts to allocate facility costs to various vehicle types, with some efforts making initial attempts to address HV traffic operations; the focus eventually shifted to PCE appropriate for traffic operations analyses. Given a focus on delay performance of signalized intersections, PCE calculation methods used various time-based variables such as: the heavy vehicle-to-passenger car **headway ratio** *(49, 50, 55, 56)* and a similar **ratio applied to travel times** *(53)*; the **additional delay due to the presence of HV** *(28)*; the **lower speeds** *(35)* **due to the presence of heavy vehicles**.

Additional investigated factors

A large number of factors have been analyzed for their effect on PCE for freeway applications. Most analyses focused on **percent trucks** in the traffic stream, followed in popularity by g**rade steepness** and **grade length** and **truck type** (based on **vehicle length** and **weight-to-power ratio)**. Other analyzed factors included the number of freeway lanes, freeway configuration (**merge, diverge or basic freeway section)**, presence of roadside maintenance activity, s**eparate speed limits for PC and HV**, and **pavement condition** (**wet or dry**; also **pavement repair state**). A summary of literature review findings is presented below.

The 1965 HCM and research efforts published shortly after its publication indicated that PCE diminish as **percent trucks** increases *(2, 11, 57, 58)*, however the issue of how to best define PCE remained unresolved for many years. A list of suggestions was provided by Huber *(1)* and discussed by other contributors to his paper. Nonetheless, the effects of **percent trucks and percent buses** have been recognized as important inputs in deciding PCE values since the early eighties.

PCE values based on a microscopic simulation package (FRESIM) that included a dynamic HV performance model was used to analyze the effect a number of vehicle and roadway geometry factors have on PCE *(29)*. The effect of **weight-to-power ratio**, **truck length**, **truck percentage**, **grade steepness**, **grade length** and **number of lanes** under **flow levels** between 500 and 2,000 vphpl were simulated for basic freeway sections. The authors demonstrated that PCE values increased with grade steepness and length; decreased with increasing truck percentage in the traffic mix, but this trend was reversed at the higher flow rates investigated. Truck weight-to-power ratio and truck length were found to have a stronger influence on PCEs on long and steep grades (resulting in higher PCE values), rather than on level sections. Number of lanes (lower PCE for more lanes) and free-flow speed did not influence PCE values to a significant degree; **truck type** was found to be critical for PCE determination.

A microscopic simulation –based study *(42)* using field data from a previous effort *(32)* produced results for queue discharge flow (QDF), calibrated on the field data. Simulation allowed expanding findings to account for **grade length and steepness** as well as **percent trucks** in the traffic stream. Increasing grade steepness and length was found to result in higher PCE values; higher truck percentages resulted in lower PCE values under identical grade geometry; this effect was found to be negligible for small and/or short grades but became more pronounced as grade steepness and length increased.

An effort simulating HV performance through a vehicle dynamics model *(40)* analyzed the effect on PCE of **percent trucks**, **grade length and steepness**, **pavement condition** (rolling resistance), **separate speed limits for trucks** and passenger cars, various **weight-to-power distributions.** This effort concluded that truck population distribution has no impact on HV PCE for grades up to 2%. Percentage of trucks has a significant impact on PCE only at low proportions—decreasing PCE values were calculated as percent trucks increased.

Simulation-based PCE values were investigated *(59)* for a one-lane work zone using **delay comparisons** between PC-only traffic and mixed traffic. Using a 1-mile-long work zone with a 10 mph **speed differential between PC and HV** this study determined that PCE decreased with increasing **truck percent.**

An extensive vehicle classification field data collection effort *(30)* analyzed PCE value relations with **hourly volume**. The analysis included PCE values corresponding to forced flow **LOS F** (defined based on the presence of speeds below 30 mph). Although PCE values were found to be higher in **merge and weave sections** than **diverge and basic freeway sections,** differences were negligible for all practical purposes.

Videotaped field data collected under queue discharge conditions as vehicles were leaving freeway bottlenecks were analyzed in order to calculate PCE values applicable under special circumstances *(32)*. PCE values were found to be unaffected by **roadside maintenance** work away from the edge of the road under dry pavement conditions. Higher PCE values were observed under **rain conditions**.

PCE equations

The 1965 HCM *(2)* introduced the term passenger car equivalent (PCE), however the discussion about the meaning and definition of the term was ongoing a decade-and-a-half later when Huber *(1)* investigated a number of potential definitions that formed the basis of a debate around the issue and served as a starting point for many research efforts in the following decades.

Estimating the value of PCE for freeway applications relies on the comparison between a "base traffic stream" comprising passenger cars only and a "mixed traffic stream" in which a proportion of trucks P_T is present *(1)*. As flow increases in each of these two traffic streams, "impedance" increases (expressed, for example, as higher traffic density, lower speed, higher volume-to-capacity ratio etc.) However, the rate of impedance increase in the mixed traffic stream for an equal increase in flow in the two traffic streams is higher due to the presence of heavy vehicles. Conversely, for a given impedance level, it is expected that a lower flow will be observed for the mixed rather than the base traffic stream. The flows in the two traffic streams that produce the same measure of impedance are related through the following fundamental equation that defines the PCE value at the chosen level of impedance:

$$q_B = (1 - P_T)q_M + P_T\, q_M(PCE) \tag{4}$$

Where:
q_B base traffic flow in pcphpl
q_M mixed traffic flow in vphpl
P_T truck proportion in mixed traffic
PCE passenger car equivalent value

Thus:

$$PCE = \frac{1}{P_T}\left(\frac{q_\mathrm{B}}{q_\mathrm{M}} - 1\right) + 1 \tag{5}$$

In 1981, studies to determine PCE values for urban arterials, rural two-lane two-way highways, and freeways (both urban and rural) were on-going. Huber *(1)* suggested that an appropriately chosen impedance measure, related to the level of service (LOS), be used to determine PCE values for each facility type.

Huber's equation ***(5)*** assumed only one type of heavy vehicle (trucks) out of the three types for which PCE values were available in the 1965 HCM (trucks, intercity buses and recreational vehicles). Equation ***(5)*** was expanded by Sumner *(28)* to arrive at PCE values for a specific heavy vehicle type (E_T) when multiple heavy vehicle types are present in the traffic stream.

$$E_{\mathrm{T}} = \frac{1}{\Delta P} \left(\frac{q_{\mathrm{B}}}{q_{\mathrm{S}}} - \frac{q_{\mathrm{B}}}{q_{\mathrm{M}}} \right) + 1 \tag{6}$$

Where:
ΔP proportion of specific heavy vehicle type in the traffic stream.
q_B base flow, in pcphpl
q_M mixed traffic flow-all truck types included, in vphpl
q_S mixed traffic flow-only the specific truck type included, in vphpl
q_B, q_M and q_S measured at the same traffic density level (pc/mi/ln, veh/mi/ln, veh/mi/ln, respectively)

Krammes and Crowley *(10)* proposed a PCE formulation that converted Huber's q_B and q_M-based equation ***(5)*** into an equivalent expression based on headways. Using the relationship between traffic flow q and headway h:

$$q_i \frac{veh}{h} = \frac{(3600\, sec/h)}{h_i \frac{sec}{veh}} \tag{7}$$

Equation ***(5)*** was transformed to the equivalent PCE definition:

$$PCE = \frac{1}{P_T} \left(\frac{h_{\mathrm{M}}}{h_{\mathrm{B}}} - 1 \right) + 1 \tag{8}$$

Where:
h_B average headway in the base traffic stream in sec
h_M average headway in the mixed traffic stream in sec
P_T truck proportion in mixed traffic
PCE passenger car equivalent value

A proposed equation incorporated previous findings about headway differences maintained by drivers following a leading vehicle depending on the types of leading and following vehicle pairs on freeways. Separate mixed traffic headway values were included for cars following trucks (h_{MPT}), trucks following cars (h_{MTP}) trucks following trucks (h_{MTT}), and passenger car-passenger car headways (h_{MPP}), using passenger car-passenger car headways in base traffic (h_{BPP}) as the basis for comparisons. Using the above-noted four separate headway values in mixed traffic, the probabilities that each of these headways would occur in a traffic stream (for example, the probability of a truck following a car is [P_T][1-P_T]), and replacing the base traffic passenger car-passenger car headway notation h_B with h_{BPP} in equation ***(8)***, the following equation was developed:

$$PCE = \left({}^{1}/_{P_T}\right)\{[\quad (1-P_T)^2 h_{M_{PP}} + P_T(1-P_T)h_{M_{PT}} + P_T(1-P_T)h_{M_{TP}} + {P_T}^2 h_{M_{TT}} - h_{M_{PP}} \quad]/h_{B_{PP}}\} + 1 \qquad \textbf{\textit{(9)}}$$

Where:
PCE passenger car equivalent value
$\boldsymbol{P_T}$ proportion of trucks in mixed traffic
$\boldsymbol{h_{X_{YZ}}}$ average headway in sec:
    X value: **M** mixed traffic; **B** base traffic
    Y, Z values: **P** passenger car; **T** truck (**Y** following vehicle; **Z** leading vehicle)

If the assumption is made that passenger car-passenger car headways in mixed traffic are equal to passenger car-passenger car headways in basic traffic, a hypothesis supported by a number of investigators *(24, 60, 61),* expressed in equation ***(10)***, that is:

$$h_{B_{PP}} = h_{M_{PP}} \qquad \textbf{\textit{(10)}}$$

Then equation ***(9)*** is simplified to:

$$PCE = \frac{\{(1-P_T)\left(h_{M_{PT}} + h_{M_{TP}} - h_{M_{PP}}\right) + P_T h_{M_{TT}}\}}{h_{M_{PP}}} \qquad \textbf{\textit{(11)}}$$

Where:
PCE passenger car equivalent value
$\boldsymbol{P_T}$ proportion of trucks in mixed traffic
$\boldsymbol{h_{X_{YZ}}}$ average headway in mixed traffic in sec:
    X value: **M** mixed traffic; **B** base traffic
    Y, Z values: **P** passenger car; **T** truck (***Y*** following vehicle; ***Z*** leading vehicle)

The advantage of this simplified equation is that it can be based on headways measured in mixed traffic without the need to establish a comparable base traffic. This makes the equation suitable for real-world mixed traffic streams where measuring passenger car-only traffic would not be feasible. Equation ***(11)*** can be further simplified depending on whether the four required headways are found to be statistically significantly different from each-other in mixed traffic.

Krammes and Crowley *(10)* analyzed actual traffic streams with traffic flows between 400 and 1,300 vphpl (corresponding to LOS A-C) and found that trucks maintained significantly longer headways from leading cars than from leading trucks. Car drivers maintained larger but not significantly so headways when traveling behind trucks compared to the headways they maintained behind cars. If these findings are translated to $h_{MPT} = h_{MPP}$ then equation ***(8)*** can be further simplified to:

$$PCE = \frac{(1 - P_T)\left(h_{M_{TP}}\right) + P_T h_{M_{TT}}}{h_{M_{PP}}} \qquad (12)$$

The authors, however, caution that this simplification may not be applicable at flow rates higher than the ones investigated in their effort.

Kockelman and Shabih *(51)* analyzed the effect light duty truck presence has on signalized intersection delay. They developed PCE values using field data and the headway-based equation below:

$$PCE_i = \frac{\delta_i + \Delta\gamma_i}{\gamma_p} \qquad (13)$$

Where:
PCE$_i$ PCE for vehicle type i
δ_i mean headway for vehicle type i in sec
γ_p mean headway for a passenger car-only queue in sec
$\Delta\gamma_i$ mean additional delay caused by the presence of a vehicle type i in the queue in sec

The numerator of equation ***(13)*** recognizes the typically longer headways required by light-duty trucks (compared to those for cars in the denominator) but also the additional delay effect a light-duty truck in the lead queue position has on the vehicles behind it as the queue starts to move at the beginning of the green phase.

Demarchi and Setti *(38)* discussed shortcomings of equation ***(5)*** by Huber *(1)* due to the presence of multiple heavy vehicle types in a typical freeway traffic stream. They proposed a modification in order to induce a smaller estimation error of the effect multiple heavy vehicles types have on PCE value calculations:

$$PCE = \frac{1}{\sum_1^n P_i} \left(\frac{q_{\mathrm{B}}}{q_{\mathrm{M}}} - 1\right) + 1 \qquad (14)$$

Where:
PCE is the proposed “aggregate equivalence factor” when **n** heavy vehicle types are present
P_i is the proportion of trucks type i in the traffic stream
q_B base flow, in pcphpl
q_M mixed traffic flow-all truck types included, in vphpl
n number of heavy vehicle types in the mixed traffic stream

MOE used for PCE calculation

The issue of defining heavy vehicle PCE for free-flowing multilane facilities was in flux in the years following the 1965 HCM publication. Various approaches were proposed and investigators extensively debated their merits and disadvantages. The following presentation follows a timeline of some of the efforts to establish the current PCE definition used in freeway operations analyses.

One often cited effort by Huber *(1)* used Greenshields traffic flow model to derive PCE values applying three separate "impedance" measures for comparisons between a base and a mixed traffic stream:

A. PCE calculations founded on equal average speeds for mixed and base traffic produced the highest PCE values under low traffic volumes and decreasing values with increasing volumes.
B. PCE calculations founded on equal densities for base and mixed traffic streams produced low PCE values for low traffic volumes and increasing values with increasing volumes.
C. PCE calculations considering equal PC speeds both in the base and in the mixed traffic streams resulted in a fixed PCE value regardless of traffic volume level.

The author stated his preference for option B because of its intuitive value: as density increases, interactions between vehicles are more restrictive and the larger size of trucks affects traffic operations to a greater degree, thus increasing PCE values would be expected, rather than the decreasing or constant PCE values that options A or C suggested.

Commenting on Huber's work *(1),* St. John stated his preference for a constant PCE value (option C) in order to reduce the need for input data and because

> "... constant PCE implies fundamental relationships that do not change in form between the car only and mixed flows."

In support of his thesis, St. John mentioned that previous efforts, showed evidence both supporting and conflicting with using constant PCE values as a function of flow rate: The 1965 HCM*(2)* showed small PCE increases with deteriorating level of service, and work based on microscopic simulation models supporting the use of one flow/speed curve for base and mixed traffic that implied a fixed PCE value over a range of flow rates had been developed *(11, 57)*. Given the ambivalence on the issue, St. John suggested that more field data- based efforts were needed to provide a definitive answer.

Machemehl commented that Huber's work *(1)* was a very good starting point in defining PCE values. It would be useful to expand it to include more than two vehicle categories and also to replace the linear PCE-speed relationship with a non-linear form. In his view, these improvements would lead to more valid PCE values. He also suggested the need for stochastic modeling.

Krammes and Crowley *(10)* provided a comprehensive discussion of fundamental issues on deciding the basis of comparison between base and mixed traffic flows. They stated that if PCE values intended to replicate driver perceptions of flow conditions between pure passenger car and mixed traffic streams, the basis for comparison should be variables that are directly evident to the driver: speed and/or density.

However, Huber's work *(1)*lead to the observation that when pure PC and mixed traffic streams operate at the same density (in veh/mi/lane), they operate at different speeds. Furthermore, even at equal densities, although the two traffic streams include the same number of vehicles per mile, the mixed traffic stream included longer vehicles, thus average distances between vehicles are shorter and thus drivers would not perceive the two conditions as equivalent.

Establishing "pure PC" and mixed traffic stream equivalency is further complicated when one recognizes that the distances drivers tend to keep from leading vehicles vary by the type of their own and the leading vehicle type. Thus the two traffic variables that drivers can directly perceive are in apparent conflict (traffic density indicating comparable conditions-equal numbers of vehicles per mile, but speeds indicating different conditions) *(24)*.

Krammes and Crowley *(10)* derived PCE values by comparing base and mixed traffic streams with equal v/c ratios, equal densities and equal spacings and proposed the use of spacings as the preferred comparison variable for level, basic freeway segments. They also derived PCE values using a headway-based equation. Inputs were separate headway values for each leading/following vehicle type combination. Vehicle types were limited to passenger cars and trucks using equation ***(8)*** provided above. The equation was applied to a mixed traffic flow and did not require a comparison to an equivalent "base" (passenger car only) flow; passenger car-to-passenger car headways in the mixed flow were assumed to be the basis for estimating truck effect. This PCE calculation method bypassed the issue of establishing comparable base and mixed traffic flows under the assumption that headways between passenger cars would not change in the presence of trucks in the traffic stream.

A wide variety of measures of effectiveness (MOE) were used in deriving PCE values based on comparisons between a "base" and a mixed-flow traffic stream: The following MOE were used to define equivalent base and mixed traffic streams: the same density *(1, 5, 10, 25, 26, 28, 29, 35)*; and its equivalent veh-hours *(16, 28, 53)*; pc speed alone; the average speed of all vehicles-- *(2, 14, 19, 20, 35, 62)*; various analytical approaches to calculate equivalent flows *(1, 10, 34)*; platoon formation *(19)*; equivalent flows under combination of flow levels and grades *(28, 29, 35)*; comparable levels of average headway *(10, 28)*.

Freeway PCE values

As described in previous sections, a wide variety of methods, data sources and congestion levels was used to compute PCE values for freeway operations. Because of the difficulty in locating an adequate number of freeway locations with desirable geometric, traffic and environmental conditions for a comprehensive data collection effort that would allow the derivation of PCE value relations with truck percentage, grade length and steepness, congestion level and other parameters, simulation was most frequently used to derive PCE values. Field data collection efforts were typically limited to level freeway segments and typically had a fixed percentage of truck traffic at any given traffic volume level. Simulation was used to expand upon the collected data. Simulation of the dynamic performance of trucks was included in some simulation packages for a more realistic representation of truck impact on traffic operations on grades.

Most efforts were limited to free-flow conditions which sometimes extended to conditions approaching capacity; few efforts analyzed forced flow conditions and very few efforts analyzed individual vehicle information; among those who did, sample sizes for HV under high-volume and/or forced flow conditions were very small.

The following paragraphs summarize some findings from the broad spectrum of analysis methods, data sources and congestion levels analyzed in order to provide benchmark values for comparisons with the present effort. The main focus of this section is on studies using field-collected data, especially those efforts that focused on analyzing congested conditions, consistent with the goals of the current effort.

The 1950 HCM *(4)* stated that each heavy vehicle was considered to be equivalent to two passenger cars; with the introduction of the PCE term in the 1965 HCM *(2)*, the influence of various geometry and traffic conditions on PCE values was recognized.

An extensive field vehicle classification data collection effort *(30)* that collected information on 287,000 individual vehicles, used the ratio of average headway for heavy vehicles to the average headway of passenger cars to define the PCE value for a given set of geometry (basic freeway section, merge, diverge or weave section) and traffic conditions (hourly volume level). Passenger cars were used as the basis for comparisons with a PCE of 1.0. It was concluded that the semi-truck PCE value did not exceeded 2.0, a value observed at volume levels of 1,800-2,000 vphpl in weaving freeway sections. However this maximum value was based on few observations (n= 152). The highest calculated semi-truck combination PCE value for basic freeway sections was 1.21 and was observed at the 1,000 to 1,499 vphpl volume range-not enough data were available for calculations at higher per-lane volumes (see **Table 1** below).

Table 1. Passenger Car Equivalent values *(30)*

	Basic freeway section	**Merge**	**Weave**
1000-1499 vphpl			
SU 2x6	1.05 (n=112)	1.15 (n=612)	1.25 (n=1439)
SU >2AX	1.05 (n=74)	1.13 (n=308)	1.45 (n=564)
Semi-trucks	1.21 (n=202)	1.31 (n=658)	1.53 (n=2254)
1500-1799 vphpl			
SU 2x6	ISS	1.40 (n=118)	1.39 (n=270)
SU >2AX	ISS	ISS	1.44 (n=137)
Semi-trucks	ISS	1.81 (n=93)	1.77 (n=384)

Notes: SU 2x6: Single-unit two-axle six tires; SU>2AX: Single-unit more than two axles; Semi-trucks: Tractor-trailer combination; ISS: Inadequate sample size.

Single-unit trucks had lower PCE values than semi-trucks. Pick-ups, utility vehicles and vans had PCE indistinguishable from passenger cars, regardless of volume level. Motorcycle, single-unit truck, bus and semi-truck PCE were sensitive to volume—PCE values increased as volume levels increased. Very few observations were available for volumes in excess of 1,500 vphpl, especially for larger vehicles. Thus, findings based on forced flow data (criterion: speeds less than 30 mph) were tentative.

Individual vehicle data collected at two six-lane basic freeway sections were used to calculate average headways maintained between passenger cars (P) and large vehicles (L) for each of the four possible leading-trailing vehicle type combinations [PT, TP, PP and TT] *(10)*. This information was used to calculate PCE values for the observed mixed traffic using the previously introduced equation ***(8)***. Calculated values ranged between 1.0 (LOS A[3]) and 2.3 (LOS C) when data were analyzed for each location and each lane. The authors suggested averaged values between 1.1 (LOS A) and 1.4 (LOS C) for practical applications with the caveat that only limited information was available at the lowest and highest analyzed flow rates, thus these values should not be considered precise.

Average PCE values in this effort were in general agreement with other findings *(2, 17, 23)*. For example, work by Sequin et al. *(23)* using the equation $PCE = \frac{h_{HV}}{h_{PC}}$ provided PCE of 1.1 and 1.4 for LOS A and C, respectively.

A field-collected data analysis *(34)* focused on PCE at capacity (LOS E). Separate information was collected for each of three vehicle types, small (S = passenger cars), medium (M = four-wheeled vehicles larger than cars), and large (L = vehicles with more than four wheels). Average headways in the mixed traffic stream were calculated for the following leading-trailing vehicle type combinations: L-S, S-L, S-S and L-L and used as inputs in the same PCE calculation formula Krammes et al. used-equation (8). A large vehicle PCE value of 1.5 was calculated; the value for medium size vehicles (as defined above) was very close to 1.0, indistinguishable from that of passenger cars.

Based on field data from two Canadian freeway locations *(32)*, PCE determination was based on an optimization algorithm that minimized the coefficient of variation of the capacity under Queue Discharge Flow (QDF). Summaries of 5-minute traffic flow data were used. The first location, with 10% trucks, had a mean PCE of 2.36 (compared to 1.50 for the HCM 2000), with 95% confidence intervals 2.20 to 2.52. No statistically significant relation was found between PCE and percent trucks. Average capacity was estimated at 2,220 pcphpl. The second location had a 3% upgrade. Summaries of 15-minute flow data were used. The location had 15% trucks.

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[3] Levels of service (LOS) were defined based on the 1985 HCM.

The mean calculated PCE was 3.21 with a 95% confidence interval range of 2.97-3.46. When PCE were analyzed separately for the AM and the PM peaks, calculated PCE values were 3.45 and 2.80 respectively (due to different driver populations, the authors claim, citing the a previous paper *(63)*. The mean capacity was found to be 2,030 pcphpl. The AM capacity was estimated at 2,117 pcphpl and the PM capacity at 1,885 pcphpl [again explained by the presence of different driver populations during each peak, citing previous findings] *(63, 64)*. The opposite direction at that location (downgrade of 3%) had a mean PCE of 2.66 with a 95% confidence interval range of 2.40-3.00 and a mean capacity of 1,968 pcphpl.

An effort based on field data using individual vehicle and five-minute aggregate statistics, collected at three urban freeway locations *(33)* operating under a wide variety of traffic conditions established the PCE values shown in **Table 2**. Vehicles were classified into three types using the FHWA 13-vehicle class scheme: passenger cars (PC = classes 2 and 3), light trucks (LT = classes 4-7) and heavy trucks (HT = classes 8-13). Average headways for the resulting nine leading vehicle-trailing vehicle types (e.g., PC following HT, PC following PC, etc.) were quantified. Findings were in general agreement with other field-based data analysis efforts: PC following PC had the shortest headways; HT following HT had the longest headways; PC following larger vehicles (LT or HT) maintained longer headways than these vehicles kept when following PC.

Table 2. Headway and PCE values *(33)*

Average Headway and PCE for Trailing-Leading Pairs			
	PC-PC	**PC-LT**	**PC-HT**
Average headway	2.06	2.89	3.36
PCE	1.00	1.41	1.63
	LT-PC	**LT-LT**	**LT-HT**
Average headway	2.77	3.25	3.61
PCE	1.34	1.58	1.75
	HT-PC	**HT-LT**	**HT-HT**
Average headway	2.82	3.66	4.6
PCE	1.37	1.78	2.23

Notes: PC = Passenger Car; LT = Light Truck; HT = Heavy Truck.

A simulation-based PCE calculation for a one-lane work zone using **delay comparisons** between PC-only traffic and mixed traffic on a one-mile-long work zone assuming a 10 mph speed differential between PC and HV found a PCE range from 2.8 to 7.7. PCE values decreased with increasing **truck percen**t and increased with **traffic volume** *(59)***.**

Concluding remarks

The issue of establishing PCE values for use in freeway operations analyses has undergone a long evolutionary process, since the first use of the PCE term in the 1965 HCM edition. A wide variety of methods to establish PCE values has historically been applied and HV performance has changed (in the direction of decreasing lb/hp ratios).

In the 2000 and the 2010 HCM editions, PCE calculations were based on comparisons of equivalent base and mixed traffic streams defined on the basis of equal traffic densities and were calibrated for level of service C (20 pc/mi/lane). Given the lack of PCE calibrated at capacity or at oversaturated conditions (LOS E or F), practitioners evaluating such conditions have to rely on the available PCE values.

Simulation was widely applied to relatively limited field databases in order to extrapolate field-observed vehicle behavior to a variety of situations (e.g., effect of grade characteristics, number of lanes, lane restrictions for HV, etc.) for which field data were not available. Although many simulation efforts were calibrated to field data for existing conditions, their benefits were somewhat mitigated by the lack of field data for calibration of extrapolated conditions.

The effect of leading-following vehicle type-specific headway characteristics and changing headway behavior with increasing congestion levels have been recognized since the eighties. These issues gave rise to the need to collect data on individual vehicle behavior across a wide range of freeway congestion levels, but also concerns about the large data sample size required to accomplish this goal.

Cited research efforts collected headways (time between the front axles of successive vehicles crossing a point on the freeway) that were used as inputs to a variety of equations in order to calculate PCE values. Some efforts collected spacing information (distance between the front axles of successive vehicles)[4]. The current HCM definition of PCE is based on a comparison between "base" and mixed traffic streams with equal traffic densities ("equivalent" traffic streams). Using this equivalency definition it should be noted that, although average distances between vehicles will be equal in the two traffic streams, average distances between the rear of leading vehicles and the front of trailing vehicles will be shorter in the mixed traffic stream due to the presence of the longer heavy vehicles. If the notion of "equivalent" traffic streams is based on drivers' perceptions, it would be reasonable to measure an adjusted headway value, that is, the time between the rear of a preceding and the front of a following vehicle crossing a specific point on the freeway. Similarly, an adjusted spacing value based on the distance between the rear bumper of the preceding vehicle and the front of the following vehicle would be appropriate.

Most field data collection efforts focused on lower traffic volume conditions (typically corresponding to levels of service A through C) with a very limited number focusing on congested conditions (levels of service D through F). The scarcity of freeway field data for congested conditions can be somewhat mitigated by work on signalized intersections since stop-and-go traffic behavior at signalized intersections bears many similarities to traffic behavior

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[4] The two types of information (time, distance between vehicles) are interchangeable if speed data are also available.

under stop-and-go freeway conditions (oversaturated conditions at LOS F). For example, additional delays (longer headways) were measured for passenger cars following trucks who start at the beginning of the green phase (compared to headways among PC-only traffic) at signalized intersections. Thus, an examination of variables found significant in establishing PCE at signalized intersections may provide useful insights into establishing PCE values for congested freeway conditions.

The present effort focus is on collecting individual vehicle field data with an emphasis on heavy vehicle behavior under congested freeway conditions. Individual vehicle data allow the calculation of separate detailed statistics for leading-following vehicle type pairs at different congestion levels.

STUDY OBJECTIVES

The current effort set out to achieve multiple objectives in order to provide a reliable analysis of the impact heavy vehicles have on traffic operations under congested freeway conditions:

1. Collect an adequately large, adequately detailed set of field data;
2. Identify the types of heavy vehicles that have a significant impact on freeway operations;
3. Derive passenger car equivalent values for heavy vehicles for a range of congestion conditions;
4. Examine current Highway Capacity Manual passenger car equivalent values in light of findings herein:
    a. Relevance of currently used vehicle types (buses, RV, trucks) in PCE calculations;
    b. Validity of current passenger car equivalent value insensitivity to speed.

DATABASE DESCRIPTION

Five basic freeway segment sites located in Milwaukee County, Wisconsin, along I-94, I-43 and US 45 were included in the study (**Table A2**). A total of 3,981,810 individual vehicle records collected through traffic counters between September 20 and October 13, 2003, were included in the database, out of which 2,645,210 vehicle pair records were used in the analysis presented herein. In addition, 75,456 five-minute traffic flow condition summaries obtained through an independent source (pavement-embedded detectors) were used to check the reliability of individual vehicle records. Database details are provided in **Appendix A**.

DATA COLLECTION OBJECTIVE

The data collection objective was to gather individual vehicle information that would include vehicle class (FHWA code, axle configuration), time stamp (date and time), location (freeway segment, lane) and speed. This information would be used to analyze heavy vehicle impact on freeway traffic operations in comparison to corresponding passenger car operations characteristics. Since the study focus was heavy vehicle performance under congested conditions, it was desired to gather the largest possible heavy vehicle sample for speeds up to 50 mph (capacity-Level of Service E-was observed in the 45-50 mph speed range). The analyzed database contained 106,288 vehicles belonging to FHWA classes 4, 5, 8 and 9 (buses, two-axle single-unit trucks, small and large semi-trucks) at speeds up to 50 mph, 84,207 of which were moving at speeds no higher than 45 mph (database details can be found in **Table A4**). Information on a total of 2,645,210 individual vehicles was included in the analysis presented herein.

DATA COLLECTION METHODOLOGY

Vehicle records were obtained from two independent sources (see **Appendix A** for details):

1. Individual vehicle information was collected through traffic counters set at five freeway locations; and,
2. Five-minute traffic operations characteristics summaries collected through pavement-embedded loop detectors, located in close proximity to the traffic counters mentioned above.

DATA RELIABILITY CHECKS

Traffic counter-collected information was cross-verified against pavement-embedded detector information at the outset of the study. Both sources of information provided the time data were collected; separate statistics were available for each lane. Individual vehicle information was compiled into five-minute traffic volume and speed summaries presented graphically for each day and each lane; similar graphs were produced for detector-based information, allowing comparisons between the two data sets. Sample graphs (**Figures A2** and **A3**) and a description of the process are presented in **Appendix A**. Excellent correspondence between the two data sets was observed, establishing confidence in the two data sources. The individual vehicle information database was used for the remainder of the analysis; five-minute summary data were not used any further.

DATA ANALYSIS DESCRIPTION

Individual vehicle records were used to compile leading/following (abbreviated to the term **lead/lag**) vehicle pairs. Vehicle class (based on the FHWA 13-vehicle class scheme presented in **Figure A1**) and vehicle position (leading or following another vehicle) were used to define vehicle pair types. Vehicle pair types with a significant presence in the traffic stream were selected for further analysis.

Twelve vehicle pair types (described in **Table B1**) were selected for analysis. They were consolidated to a final list of ten pairs (see **Table C1**), based on similarities between two sets of pairs (details on consolidation criteria are provided on **page B2**).

Headway statistics for each of the ten lead/lag vehicle pair types were produced for each of the following nine speed ranges: Up to 20 mph; 20-25 mph; 25-30 mph; 30-35 mph; 35-40 mph; 40-45 mph; 45-50 mph; 50-55 mph; and 55+ mph. Observed headway means and 95% confidence intervals are summarized in graphical form (**Figures B1** to **B9**) in **Appendix B**, which also presents numeric findings on the statistical significance of differences between means using the Bonferroni statistic (**Tables B2** to **B10**). This information provided the necessary inputs for passenger car equivalent calculations based on the following headway ratios:

$$PCE_{i,j} = \frac{H_{i,j}}{H_{pc,j}}$$

Where:
i is a specific vehicle type (for example a 2-axle truck)
j is a specific set of physical, traffic and environmental conditions
$H_{pc,j}$ is the mean passenger car headway under conditions j
$H_{i,j}$ is the mean headway for vehicle type i under conditions j
$PCE_{i,j}$ is the passenger car equivalent for vehicle type i under conditions j

Headway descriptive statistics (number of cases, mean, standard deviation, standard error, and 95% confidence interval limits) are presented in **Appendix C**, **Tables C2-C11**. The same Appendix also provides passenger car equivalent values for all analyzed lead/lag vehicle pairs at all analyzed speed ranges (**Table C12**).

Headway relations with speed were examined for two broad lead/lag vehicle pair type groups: headways heavy vehicles kept from passenger cars and those kept by passenger cars when following heavy vehicles and are presented in **Figures C1** and **C3**, respectively. Passenger car equivalent relations with speed for the same two vehicle pair type groups are presented in **Figures C2** and **C4**, respectively.

FINDINGS

The present effort focused on an analysis of the influence heavy vehicle presence on freeways has on headways between vehicles in the traffic stream. It was shown that vehicle position (as either a leading or a following vehicle), vehicle class and speed significantly affect headways and thus passenger car equivalent values.

It was decided at the outset of this analysis to limit its scope to maximum values of 65 mph, 30 sec headways and 600 ft spacing (see **page A3** for details). Headways that passenger car drivers kept from leading passenger cars or pickups/vans were found to be statistically indistinguishable and were examined as a single headway population. For the same reason, headways that pick-up/van drivers kept from leading passenger cars were consolidated with those they kept from other pick-ups/vans (see **page B3** for details).

Findings are presented in the following four subsections: heavy vehicles following passenger cars, passenger cars following heavy vehicles, passenger cars in a leading versus a following position in a vehicle pair and a summary of findings.

Heavy vehicles following passenger cars

Heavy vehicles following passenger cars kept the longest **headways** at the lowest speeds (up to 20 mph-**Table C11 and Figure C1**). Listed in longest to shortest headway order, two-axle single-unit trucks (vehicle class 5)[5] kept 5.7 sec; heavy semi-trucks (class 9) and buses (class 4) were similar at 4.8 and 4.7 sec, respectively; lighter semi-trucks (class 8) kept 3.8 sec; pick-ups/vans (class 3) 3.6 sec; and, passenger cars (class 2) 3.1 sec.

- Passenger car headways were the shortest of all analyzed vehicle pair types at all speed ranges.
- Pick-up/van headways followed a trend paralleling that of passenger cars but with higher values ranging from +0.50 sec at speeds up to 20 mph, about +0.20 sec between 20 and 50 mph and about +0.05 sec at higher speeds.
- Small semi-truck headways fell between those of passenger cars and those of pickups/vans for speeds between 20 and 45 mph; they exceeded those of pick-ups/vans by no more than 0.2 seconds at speeds outside this range;
- Small semi-truck headways were not statistically significantly different than passenger car headways for speeds between 20 and 40 mph.[6]
- Small semi-truck headways were significantly shorter than those of buses, two-axle single-unit trucks and large semi-trucks for speeds up to 55 mph.
- Headways decreased rapidly as speeds increased to 35 mph.

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[5] See **Figure A1**

[6] See **Tables B3** through **B6**

  - Passenger car, pick-up/van and small semi-truck headways continued to decrease as speeds increased to 50 mph, after which point they started increasing.
  - Large semi-truck headways continued to decrease with increasing speed over 35 mph, albeit at a lower rate.
  - Bus and two-axle single-unit truck headways exhibited minor fluctuations at speeds above 35 mph.

The highest ***passenger car equivalent*** (PCE) values for **heavy vehicles following passenger cars** were observed at speeds up to 20 mph (**Table C12** and **Figure C2**). Two-axle single-unit trucks lead with a PCE = 1.81, followed by large semi trucks (1.54) and buses (1.52). Small semi trucks had a much lower PCE value (1.22), much closer to that of pickups/vans (1.15) than to those of larger vehicles.

- Buses and large semi-trucks exhibited somewhat similar PCE patterns with increasing speed: there was a drop for speeds 20-25 mph (to PCE of 1.28 and 1.53, respectively), minor fluctuations between 25 and 35 mph and a peak somewhere between 40 and 50 mph (PCE 1.51 and 1.72, respectively), after which values dropped to reach their lowest levels at the highest speeds examined (1.23 and 1.27, respectively).
- PCE values for two-axle single-unit trucks dropped significantly at speeds of 20-25 mph to 1.32 and had minor fluctuations until 55 mph (1.26); they declined to 1.11 at higher speeds.
- Small semi-truck PCE values dropped to the 1.00 level for speeds 20-30 mph at which point they started a gradual increase up to speeds of 55 mph (PCE = 1.11). A minor decrease was evident for higher speeds (1.09).
- Pick-ups/vans remained consistently close to a PCE of 1.09 for speeds 20-55 mph, with a minor decline to 1.02 for higher speeds.

Passenger cars following heavy vehicles

Passenger cars following heavy vehicles kept the longest **headways** for speeds up to 20 mph (**Table C11 and Figure C3**); buses and small semi-trucks had the highest headways (5.70 and 5.67 sec, respectively), followed by large semi-trucks (5.11 sec), two-axle single-unit trucks (3.98 sec) and passenger cars (3.13 sec).

- Headways decreased with increasing speed and reached their lowest values in the 45-50 mph range, after which point they started increasing, paralleling the passenger car-following-passenger car trend.
- Headways kept from buses, small and large semi-trucks were very similar for all speeds reaching minimum values of 2.13 to 2.30 sec at speeds 45 to 50 mph.
- Headways kept from two-axle single-unit trucks were significantly shorter than those kept from buses, small and large semi-trucks within all analyzed speed ranges. The shortest headways (1.88 sec) were observed at 45-50 mph.
- Headway differences between following two-axle single-unit trucks and following any of the other analyzed heavy vehicle classes generally decreased with increasing speed.

Passenger car equivalent values for all types for **passenger cars following heavy vehicles** were highest for speeds up to 20 mph (**Table C12 and Figure C4**). Values were similar when following small semi-trucks and buses (1.81 and 1.82, respectively); the value was 1.63 following large semi-trucks; A much lower value (1.27) was associated with following two-axle single-unit trucks.

- Passenger car equivalent values generally declined with increasing speeds.
- PCE values for passenger cars following semi-trucks and buses were very close for speeds greater than 25 mph, with nearly identical values within the 30-35 mph speed range (1.46 to 1.47), and also for speeds exceeding 55 mph (1.16 to 1.18).
- PCE values based on following two-axle single-unit trucks were quite lower at every speed; a value of 1.04 corresponded to speeds higher than 55 mph.

Leading vs. following passenger cars

Differences in driver behavior depending on their vehicle position in a lead/lag vehicle pair are summarized in **Figure C5**. The vertical axis represents the following difference of average headways (in sec): ***average headway when a passenger car leads minus average headway when a passenger car follows***. When both vehicles are passenger cars this difference is zero (shown with a thick horizontal line on **Figure C5**. If the headway a trailing heavy vehicle type keeps from a leading passenger car at a given speed (for example the headway for lead/lag vehicle pair type 205[7] in **Table C11** is 5.66 sec) is longer than the headway a trailing passenger car keeps from the same heavy vehicle type (pair type 502 in **Table C11** at 3.98 sec), the difference is positive. When the reverse is true for the headway relationship, the difference is negative.

Thus, **Figure C5** indicates that passenger car drivers kept longer headways from leading small semi-trucks than semi-trucks kept from leading passenger cars; also, that passenger car drivers kept shorter headways from leading two-axle single-unit trucks than these trucks kept when following passenger cars. These findings were true for all analyzed speed ranges. At lower speeds, passenger car drivers kept longer headways from leading buses and large semi-trucks than these vehicles kept from passenger cars. As speeds increased the headway relation was reversed, beginning at the 20-25 mph speed range for large semi-trucks and at the 35-40 mph speed range for buses.

Summary of findings

Headways between vehicle pairs were at their maximum values for speeds up to 20 mph and declined sharply for speeds 20-25 mph, after which point they still declined but at a lower rate as speeds increased to 50 mph. At higher speeds headways between most analyzed vehicle pair types increased; they remained almost constant when two-axle, single-unit trucks, buses or large semi-trucks were following passenger cars.

Average passenger car-to-passenger car headways were the shortest among all examined lead/lag vehicle pair types at each examined vehicle speed range. Small semi-trucks and pick-ups/vans

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[7] Vehicle pair type 205: Passenger car (vehicle class 2) followed by a two-axle single-unit truck (vehicle class 5).

following passenger cars maintained very similar headways to those maintained between passenger cars.

Passenger car drivers maintained very similar headways when following buses and semi-trucks; they kept shorter headways from two-axle single-unit trucks.

Among heavy vehicles following passenger cars, passenger car equivalent (PCE) values for pick-ups/vans and small semi-trucks were very close for all analyzed speeds. PCE values were increasingly higher for two-axle single-unit trucks, buses and large semi-trucks (in this order) for speeds higher than 25 mph.

PCE values based on passenger cars following heavy vehicles decreased with increasing speed. The lowest values were associated with following two-axle single-unit trucks; values for buses and semi-trucks were significantly higher and very close together for all speeds.

Passenger car drivers kept longer headways than their heavy vehicle counterparts when following: small semi-trucks at any speed; buses for speeds up to 35 mph; large semi-trucks for speeds up to 20 mph. Passenger car drivers kept shorter headways than their heavy vehicle counterparts when following: two-axle single-unit trucks at any speed; buses at speeds above 40 mph; and large semi-trucks at speeds above 25 mph.

DISCUSSION

Heavy vehicle passenger car equivalent values appropriate for application under congested freeway conditions were calculated based on headway information. Passenger car equivalent values for a specific heavy vehicle class have typically been based on average headways kept by this vehicle class from leading vehicles. The ratio of heavy vehicle headways (or equivalent traffic flow variable) to those of passenger cars was typically used to arrive at passenger car equivalent values for a specific heavy vehicle class.

Recognizing that headways are affected by the vehicle class of both the leading and the following vehicle, the present effort focused on the analysis of headways for the most prevalent leading/following vehicle pair types, (defined based on the vehicle class of each vehicle in a pair).

Heavy vehicle impact on traffic operations (measured through their impact on headways) was shown to depend on heavy vehicle class (semi-trucks, bus, single-unit two-axle truck), whether the heavy vehicle was leading or trailing a smaller vehicle, and vehicle speed.

Some noteworthy headway differences were identified between lead/lag vehicle pair types involving a passenger car and a different type of vehicle, depending on whether the passenger car was in the leading or the following position in a pair. This was evident, for example, in the case of vehicle pair types 208 and 802 (small semi-truck following a passenger car and passenger car following a semi-truck, respectively): Semi-truck drivers kept headways about equal to those kept by passenger car drivers following a passenger car (**Figure B2**), however, passenger car drivers kept much longer headways from leading semi-trucks.

Headway differences kept by drivers depending on their speed and the class of the vehicle they drive are summarized in **Figure C5**. The average headway kept by passenger car drivers when following passenger cars was used as the basis for comparison (zero headway difference). Under the conditions examined herein (basic freeway section, level terrain) and at low speeds, drivers of passenger cars following semi-trucks or buses were found to keep longer headways than those heavy vehicles kept from passenger cars. In comparison to the headways kept by passenger car drivers following heavy vehicles, small semi-truck drivers kept shorter headways driving behind passenger cars, and two-axle single-unit truck drivers kept longer headways for all examined speeds. For large semi-trucks and buses following passenger cars the situation was mixed: their drivers kept shorter headways than passenger car drivers kept from these vehicles at lower speeds (up to 20 mph and up to 35 mph, respectively) and longer headways at higher speeds.

When headways of various vehicle classes are examined ignoring the effect leading vehicles have, it is commonly assumed that the longer headways associated with heavy vehicles are due to their inferior acceleration/deceleration performance and their larger sizes. However, the present analysis indicated that passenger car headways sometimes exceed those of heavy vehicles, especially at low speeds. These longer headways cannot be attributed to inferior passenger car performance or size. A more likely explanation may be that passenger car drivers following heavy vehicles in slow traffic are possibly attempting to improve their sight distance to objects ahead of their vehicles, or looking for an opportunity to change lanes, , thus deliberately creating enough distance in front of their vehicles to be able to increase their sight distance and/or accelerate as they change lanes.

The developed passenger car equivalent values for specific leading/following vehicle pair types presented in **Table C12** were based on the ratio:

$$PCE_{i,j} = \frac{H_{i,j}}{H_{pc,j}}$$

Where:
i is a specific vehicle type (for example a 3-axle truck)
j is a specific set of physical, traffic and environmental conditions
$H_{pc,j}$ is the mean passenger car headway under traffic and environmental conditions j
$H_{i,j}$ is the mean headway for vehicle type i under traffic and environmental conditions j

Passenger car equivalent values in **Table C12** were computed for each analyzed speed range. The average headway between two passenger cars within a speed range was used as the denominator in the above-mentioned ratios; the average headway between vehicles in a specific leading/following vehicle pair type was used as the numerator.

The suggested passenger car equivalent value for level basic freeway segments in the 2010 HCM is 1.5 for trucks and buses ($E_T = 1.5$) and recreational vehicles ($E_R = 1.5$). This value was calibrated on freeway operations at levels of service A through C. The values shown on **Table C12** indicate that the suggested HCM values may be overly conservative (high) compared to the values shown for speeds in the over-55 mph column that include LOS A-C conditions (capacity

= LOS E was observed at speeds of 45-50 mph). Calculated PCE values were lower than 1.5 for speeds 30 mph and above with minor exceptions for buses and large semi-trucks following passenger cars. However, for speeds lower than 30 mph PCE values higher than 1.5 were present for passenger cars following buses and semi-trucks, also for large semi-trucks following passenger cars. Buses and two-axle single-unit trucks following passenger cars had PCE values higher than 1.5, as well.

CONCLUSIONS

Headways

In this section, the term "headway" associated with a specific vehicle class implies that the vehicle is in the following (not the leading) position in a vehicle pair. All examined vehicle pairs included at least one passenger car. Sources for this section are **Figures C1** and **C3** and **Table C11**.

- Headway behavior depended to a significant extent on the specific pairs of leading/following vehicles in a traffic stream.
- Headways increased sharply at very low speeds regardless of leading/following vehicle pair type.
- Passenger cars headways declined sharply as speeds increased up to 30 mph; the decline continued at smaller decrements for speeds up to 50 mph, after which point they tended to increase again.
- The shortest headways were between two passenger cars at all speeds.
- Two-axle single-unit truck drivers kept longer headways than passenger car drivers at all speeds.
- Small semi-truck drivers kept shorter headways than passenger car drivers at all speeds.
- Findings were mixed for large semi-truck and bus headways: passenger car headways were longer at lower speeds (up to 20 mph and up to 35 mph, respectively) and shorter at higher speeds (above 25 mph and above 40 mph, respectively).
- Small semi-truck headways were very similar to passenger car (to passenger car) and pick-up/van headways.
- Large semi-trucks, buses and two-axle single-unit trucks kept significantly longer headways than small semi-trucks.

Passenger Car Equivalents

Passenger car equivalent values for heavy vehicles following passenger cars **(Figure C2)**:

- Were the highest at speeds up to 20 mph with the exception of large semi-trucks.
- Declined sharply as speeds increased to 25 mph.

- Exhibited fluctuations specific to each vehicle class for speeds up to 35 mph at which point values start increasing, reaching a maximum between 40 and 50 mph; they declined for higher speeds.
- Large semi-trucks had the highest values, followed by buses and two-axle single-unit trucks in this order.
- Small semi-truck values were very close to those of pick-ups/vans for all examined speeds and not different than 1.00 for speeds between 20 and 30 mph.

Passenger car equivalent values for passenger cars following heavy vehicles **(Figure C4)**:

- Declined with increasing speed.
- Values observed when following semi-trucks (both small and large) or buses were very close at all speeds; they were higher than the values observed when following two-axle single-unit trucks at all speeds.

RECOMMENDATIONS

The headway analysis in the present effort was based on statistics collected for ten lead/lag (leading/following) vehicle pair types for speeds up to 65 mph. This in-depth view of headway driver behavior allows a more accurate representation of the speed-volume-traffic density relationships, which extends into congested conditions, which were not addressed in any depth in the current (2010) Highway Capacity Manual. Estimates of the prevalence of each lead/lag vehicle pair type can be used in analyzing freeway operations for planning purposes; use of exact counts from vehicle classification stations would be recommended for use in freeway operations analyses of existing freeway facilities in order to develop facility-specific speed-volume-traffic density relationships reflecting existing traffic composition.

Findings in the present effort are especially useful in micro-simulation efforts. Headway information for particular leading/following vehicle pair types at each speed range can be used to calibrate car-following models to accurately represent real-world traffic conditions. The findings, for example, which passenger car drivers keep long distances when following larger vehicles, or that small semi-trucks (vehicle class 8) keep headways very similar to those observed between passenger cars, may be overlooked in a pure dynamic simulation model. Dynamic heavy vehicle performance-based headway simulation values can benefit from cross-checking against field-based information provided herein.

Whether the professional's interest is in planning or operations freeway analyses, or freeway simulations, it is recommended that present effort headway and/or passenger car equivalent findings be used, since they address headway information under congested traffic conditions, an area in which the Highway Capacity Manual does not currently provide detailed guidance.

Headway and passenger car equivalent values derived through the present effort are suitable for addressing conditions at many urban freeways currently operating at capacity or even at Level of Service F. Freeway construction zones often result in similar conditions due to lane closures or general construction-related activities; Departments of Transportation can benefit from the present effort in establishing work zone transportation management plans.

The present report provides passenger car equivalent values based on headway ratios. Findings can be converted to other potential passenger car equivalent definitions, for example, if a traffic density-based passenger car equivalent relationship is desired, the relationship between traffic density, volume and speed can be used to achieve this goal.

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Appendix A

Study Database

INTRODUCTION

An objective of the present effort was to gather a large number of individual heavy vehicle records operating under congested freeway conditions. An extensive effort that included contacts with the FHWA, state DOT personnel and various vehicle classification data collection equipment manufacturers was launched to identify suitable data sources. FHWA provided access to national vehicle classification data sets maintained in various formats and the list of state DOT personnel assigned to maintaining vehicle classification data, presented in **Table A1**.

Despite the above-described efforts it was not possible to locate datasets containing individual vehicle records for the following typical reasons:

1. Vehicle classification data available from FHWA or state DOTs were maintained in various summary forms (hourly, daily, monthly)[8];
2. Some states had no congested urban freeway sections;
3. States with congested urban freeways typically placed automated vehicle classification stations in outlying urban areas where speeds were high[9]—data from such locations would not meet the objectives of the present study.

Requests to collect data explicitly for the purposes of the present study from a few urban congested freeway locations with the ability to record per-vehicle records were turned down due to: lack of data-gathering network bandwidth capacity to perform this task; the disruption to the normal field data-gathering schedule; and, a lack of personnel availability to take this extra task on.

Vehicle classification equipment manufacturers/vendors were contacted in order to verify equipment capabilities and obtain DOT contact information. However, where potentially useful locations equipped with appropriate equipment were identified, the practical problems with data storage, communications limitations and personnel availability described herein precluded the collection of per-vehicle records.

Thus, the analysis focused on data collected in 2003 at Milwaukee County, Wisconsin, urban basic freeway sections. A Milwaukee County freeway system map with 2003 Average Daily Traffic information is provided in **Figure A4.** Sections where low speeds during peak periods were a common occurrence were selected for analysis and are described in the next section.

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[8] Cited reasons were: FHWA—information is used to identify long-term/state- or nation-wide heavy vehicle trends, it is not intended for traffic operations applications; State DOTs—data storage capacity limitations and/or limited bandwidth available for multiple field-placed detectors to communicate with DOT data monitoring facilities and/or no interest in using such information for day-to-day freeway operations functions.

[9] Cited reasons were: lower traffic volumes allowed easier access to in-pavement equipment in case of malfunction; the purpose of data collection was to monitor heavy vehicle traffic trends, not managing freeway operations.

STUDY DATABASE

Data analyzed in this effort were collected at the urban Milwaukee County, Wisconsin, freeway locations described in **Table A2** between September 20 and October 10, 2003. Data were collected through two independent sources of information:

1. Pavement-embedded loop detectors; and,
2. Portable traffic counters.

Locations experiencing low speeds, the focus of the present effort, were targeted for analysis. Information was analyzed using dual speed and volume axes figures similar to **Figures A1** and **A3** in order to identify the extent of data availability from each source. Barring hardware outages, pavement-embedded loop detectors collected information continuously; counters were typically used continuously for approximately one week at each location. It should be noted that pavement-embedded detectors were placed in the vicinity, but not the exact same location as portable traffic counters. Information was available for each individual lane from both data sources.

DATABASE STATISTICS

A total of 3,981,810 individual vehicle observations were available for analysis from portable traffic counters. Vehicles belonging to each of the thirteen vehicle classes in the FHWA scheme in **Figure A1** were represented in the database. Vehicle class distribution is shown in **Table A3**.

A total of 75,456 five-minute speed and volume summary data were available from pavement detectors; traffic counter data provided 50,954 five-minute summaries. The difference in numbers of observations between the two databases was due to: a) two pavement-embedded locations used to verify the traffic counter information at the 84th Street I-94 location, and, b) occasional data unavailability due to various hardware problems.

A summary of the number of vehicles recorded within each vehicle class, moving at a given speed range is provided in **Table A4**. A total of 72,277 heavy vehicles in classes 4 through 9 were recorded for speeds up to 40 mph; 84,207 such vehicles were recorded for speeds up to 45 mph and 106,288 for speeds up to 50 mph. Freeway capacity (level of service E) occurred between 45 and 50 mph. Very few heavy vehicles in classes 6, 7 and 10 through 13 were observed; these vehicle classes were not included in the headway analysis.

After reliability checks described in the next paragraph were performed, vehicles traveling at speeds above 65mph, those keeping headways longer than 30 seconds or spacing greater than 600 ft were dropped from further consideration. It was decided that such conditions represented free-flow or near free-flow conditions and were outside the scope of the present project. Vehicles in classes 1, 6, 7, and 10-13 were also dropped from further consideration in order to simplify the analysis, given their minimal presence in the traffic stream. Leading/following vehicle pairs were established for the 12 vehicle pair types shown in **Table B1**; those were consolidated to the 10 types presented in **Table C1** for the final analysis. Statistics for the analyzed vehicle pair types are presented in **Tables B2 –B10**.

DATA RELIABILITY CHECKS

Traffic counter-collected information was cross-verified against pavement-embedded detector information at the outset of the study. The two sources of information could be synchronized based on time data stamps available for each data source; it was possible to verify statistics for each lane separately.

Individual vehicle information was compiled into five-minute traffic volume and speed summaries presented graphically for each location, each day and each lane; similar graphs were produced for detector-based information, allowing comparisons between the two data sets. Sample graphs are presented in **Figures A2** and **A3**.

Figures A2 and **A3** present traffic counter and pavement-embedded detector data, respectively, for the same dates and show excellent correspondence between the two data sets, especially for traffic volumes (it should be kept in mind that data were collected at different locations within a given basic freeway segment, thus, although volumes should match, speeds may differ slightly).

Once the reliability of the individual vehicle information database was established, five-minute summary data were not used any further and the analysis proceeded with the establishment of headways for the lead/following vehicle pair types described in **Appendix B**, based on individual vehicle ("per-vehicle") information.

Table A1. State Department of Transportation vehicle classification contact person information

State	First Name	Last Name	Employer	Work Phone	Email Address
Alabama	Charles	Turney	DOT	334-242-6393	turneyc@dot.state.al.us
Alabama	Mike	Jones	DOT	334-242-6550	jonesmi@dot.state.al.us
Alaska	MaryAnn	Dierckman	DOT	907-465-6993	maryann_dierckman@dot.state.ak.us
Alaska	Sean	Jordon	DOT		sean_jordon@dot.state.ak.us
Alaska	Mistee	Vinzant	DOT	907-465-6974	mistee.vinzant@alaska.gov
Arizona					
Arkansas	Brenda	Haley	DOT	501-569-2204	brenda.haley@arkansashighways.com
Arkansas	El Marie	Barnes	DOT	???	elmarie.barnes@arkansashighways.com
California	Joe	Avis	DOT		joe_avis@dot.ca.gov
California	Mitchell	Prevost	DOT		mitchell_prevost@dot.ca.gov
California	Viki	Duncan	DOT	916-654-5032	viki_duncan@dot.ca.gov
Colorado	David	Smith	DOT	303-757-9816	david.e.smith@dot.state.co.us
Colorado	Steven	Abeyta	DOT	303-757-9815	steven.abeyta@dot.state.co.us
Colorado	Lina-Thuy	Nguyen	DOT	???	Thuy.Nguyen@dot.state.co.us
Colorado	Leo	Livecchi	DOT	303-757-9498	leo.livecchi@dot.state.co.us
Connecticut	John	Quinn	DOT	860-594-2119	john.quinn@po.state.ct.us
Connecticut	Daniel	Woods	DOT	860-594-2090	daniel.woods@po.state.ct.us
Connecticut	Jacqueline	Henry-Rafiq	DOT	860-594-2089	jacqueline.henryrafiq@po.state.ct.us
Connecticut	Kerry	Ross	DOT	860-594-2087	kerry.ross@po.state.ct.us
Delaware	Tyrone	Crittenden	DOT	302-760-2162	tcrittenden@state.de.us
Delaware	Paul	McKenna	DOT	302-760-2579	pmckenna@state.de.us
Florida	Walton	Jones	DOT		walton.jones@dot.state.fl.us
Florida	Ronnie	Price	DOT	850-414-4712	ronnie.price@dot.state.fl.us
Florida	Rick	Reel	DOT		richard.reel@dot.state.fl.us
General - National	Steven	Jessberger	Other	202-366-5052	steven.jessberger@dot.gov
General - National	Ralph	Gillmann	Other	202-366-5042	ralph.gillmann@dot.gov
General - National	David	Jones	Other	202-366-5053	david.jones@dot.gov
Georgia	Valorette	Coe	DOT	770-986-1444	valarette.coe@dot.state.ga.us
Georgia	Jason	Wagnon	DOT	770-686-1438	jason.knight@dot.state.ga.us
Georgia	Scott	Knight	DOT		scott.knight@dot.state.ga.us
Georgia	Catrice	Brewer	DOT	770-986-1365	catrice.brewer@dot.state.ga.us
Georgia	Trinh	Nguyen	DOT	770-986-1436	trinh.nguyen@dot.state.ga.us
Georgia	Sy	Nguyen	DOT		sy.nguyen@dot.state.ga.us
Georgia	Vanessa	Mercier	DOT	770-986-1364	vanessa.mercier@dot.state.ga.us
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Hawaii	Jeniffer	Arinega	DOT	???	jennifer.arinaga@hawaii.gov
Hawaii	Goro	Sulijoadikusum	DOT	808-587-1839	sulijoadikusumo@hawaii.gov
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Idaho	Scott	Fugit	DOT	208-334-8207	scott.fugit@itd.idaho.gov
Idaho	Glenda	Fuller	DOT	208-334-8217	glenda.fuller@idt.idaho.gov
Illinois	Rob	Robonson	DOT	217-785-2353	rob.robinson@illinois.gov
Illinois	Ramon	Taylor	DOT	217-782-2065	ramon.taylor@illinois.gov
Indiana	Marcia	Gustafson	DOT	317-232-5134	mgustafson@indot.in.gov
Iowa	Phillip	Meraz	DOT	515-239-1526	phillip.meraz@dot.state.ia.us
Iowa	Andrew	Short	DOT		andrew.short@dot.state.ia.us
Kansas	Scot	Keil	DOT	785-291-3536	scotk@ksdot.org
Kansas	Mark	Maddox	DOT	785-296-6357	maddux@ksdot.org
Kentucky	Ted	Know??	DOT	???	
Kentucky	Melissa	Brown	DOT	502-564-7183	melissap.brown@ky.gov

Table A1. (Continued) State Department of Transportation vehicle classification contact person information

State	First Name	Last Name	Employer	Work Phone	Email Address
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Kentucky	Debbie	Watson	DOT	502-564-7183	debbie.watson@ky.gov
Kentucky	Jeffery	Young	DOT	502-564-7183	jeff.young@ky.gov
Louisiana	Roger	Kennedy	DOT	225-242-4560	rogerkennedy@dotd.louisiana.gov
Louisiana	Joan	Black	DOT	225-242-4557	joanblack@dotd.louisiana.gov
Louisiana	Jim	Porter	DOT	225-358-9107	jimporter@dotd.louisiana.us
Maine	Ron	Cote	DOT	207-624-3602	ron.cote@maine.gov
Maine	Debbie	Morgan	DOT	207-624-3606	deborah.morgan@maine.gov
Maryland	Abhay	Nigam	DOT	410-545-5506	anigam@sha.state.md.us
Maryland	Jerry	Einolf	DOT	410-545-5514	jeinolf@sha.state.md.us
Massachusetts	Bill	Mitchell	DOT	508-668-8708	William.mitchell@state.ma.us
Massachusetts	Stephen	Greene	DOT	617-973-7327	stephen.greene@state.ma.us
Michigan	Melissa	Carsweel	DOT		carswellm@michigan.gov
Michigan	Mike	Walomachi	DOT	517-335-2914	???
Michigan	Teresa	Logan	DOT	517-335-6740	logant@michigan.gov
Michigan	Dave	Schade	DOT	517-335-2914	schaded@michigan.gov
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Minnesota	Kou	Vang	DOT	651-215-1115	kou._vang@dot.state.ms.us
Minnesota	George	Cepress	DOT	651-296-0217	???
Minnesota	Mark	Novak	DOT	651-296-2607	???
Minnesota	Bill (Oscar)	Martinson	DOT	651-366-3863	bill.martinson@dot.state.mn.us
Minnesota	Bruce	Moir	DOT	651-366-3865	bruce.moir@dot.state.mn.us
Mississippi	Monica	Ramsey	DOT	601-359-7714	mramsey@mdot.state.ms.us
Mississippi	T.	Trinh	DOT	601-359-7685	ttrinh@mdot.state.ms.us
Mississippi	James	Warren	DOT	601-359-7685	jwarren@mdot.state.ms.us
Missouri	Darla	Fischer	DOT	573-751-2842	darla.fischer@modot.mo.gov
Missouri	Doug	Struemph	DOT	573-751-2784	douglas.struemph@modot.mo.gov
Missouri	Mary	Kladiva	DOT	573-526-4907	mary.kladiva@modot.mo.gov
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Montana	Danny	Haynes	DOT	406-444-6122	dhaynes@mt.gov
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New Mexico	Juan	Martinez	DOT	505-827-5524	juan.martinez@state.nm.us
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New Mexico	Joshua	McClenahan	DOT		joshua.mcclenahan@state.nm.us
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Table A1. (Continued) State Department of Transportation vehicle classification contact person information

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North Carolina	Evelyn	McLamb	DOT		esmclamb@dot.state.nc.us
North Carolina	Oius	Pasquariello	DOT	919-212-4540	lpasquariella@dot.state.nc.us
North Carolina	Steve	Piotrowski	DOT	919-212-4540	spiotrowski@dot.state.nc.us
North Carolina	Shaneka	Mangum	DOT	919-212-4525	snmangum@dot.state.nc.us
North Carolina	D	Neathery	DOT		dneatherly@dot.state.nc.us
North Carolina	Kent	Taylor	DOT	919-212-4550	kltaylor@dot.state.nc.us
North Dakota	Bob	Shjeflo	DOT	701-328-1893	rdshejeflo@nd.gov
North Dakota	Terry	Woehl	DOT	701-328-3531	twoehl@dot.state.nd.us
North Dakota	Zdravka	Zeric	DOT	701-328-4426	zzeric@nd.gov
North Dakota	Bob	Olzweski	DOT	701-328-3479	rolzweski@nd.gov
Ohio	Linsey	Pflom	DOT	???	lindsey.pflum@dot.state.oh.us
Ohio	Diane	Boso	DOT	614-752-5750	diane.boso@dot.state.oh.us
Ohio	Dave	Gardner	DOT	614-752-5740	dave.gardner@dot.state.oh.us
Ohio	Tony	Manch	DOT	614-466-3075	tony.manch@dot.state.oh.us
Oklahoma	Aaron	Fredrick	DOT	405-521-2513	afridrich@odot.org
Oklahoma	John	Mitchell	DOT	405-522-3860	jmitchell@odot.org
Oklahoma	Mike	Woodhams	DOT	405-522-3793	mwoodhams@odot.org
Oregon	Tricia	Tanner	DOT	503-986-4159	tricia.j.tanner@odot.state.or.us
Oregon	Dara	Gayler	DOT	503-986-1453	dara.gayler@odot.state.or.us
Oregon	Don	Crownover	DOT	503-986-4132	don.r.crownover@odot.state.or.us
Pennsylvania	Leslie	McCoy	DOT	717-787-4574	lemccoy@state.pa.us
Pennsylvania	Jermey	Freeland	DOT	717-787-2939	jfreeland@state.pa.us
Pennsylvania	Andrea	Bahoric	DOT	717-705-2382	abahoric@state.pa.us
Pennsylvania	Steve	Howrylak	DOT	??	showrylak@state.pa.us
Pennsylvania	Todd	Rottet	DOT	717-787-4574	trottet@state.pa.us
Puerto Rico	Aramis	Martinez	Other	787-729-1581	???
Puerto Rico	Felix	Ronrigus	Other	787-766-5600	???
Rhode Island	David	Doyle	DOT	401-222-2694	ddoyle@dot.ri.gov
Rhode Island	Michael	Sprague	DOT	401-222-2694	msprague@dot.ri.gov
Rhode Island	Paul	Annarummo	DOT	401-222-2694 e	pannarum@dot.ri.gov
South Carolina	Ed	Bethea	DOT	803-737-1467	betheaea@dot.state.sc.us
South Carolina	James	Teeter	DOT	803-737-3213	teeterjr@scdot.org
South Carolina	Tammy	Stoneburner	DOT	803-737-1674	stoneburth@dot.state.sc.us
South Dakota	Stacy	Eargle	DOT	803-737-1673	earglesa@scdot.org??
South Dakota	Ken	Marks	DOT	605-773-5026	ken.marks@state.sd.us
South Dakota	Noel	Pothast	DOT	605-773-3339	noel.pothast@stae.sd.us
South Dakota	Darin	Charlson	DOT	605-773-5026	darin.charlson@state.sd.us
Tennessee	Lia	Prince	DOT	615-741-2934	lia.prince@state.tn.us
Tennessee	Bill	Anderson	DOT	615-253-8389	bill.anderson@state.tn.us
Tennessee	Steve	Allen	DOT	615-741-2208	steve.allen@state.tn.us
Tennessee	Mickey	Phelps	DOT	615-532-3387	mickey.phelps@state.tn.us
Texas	Betty	Hohensee	DOT	512-486-5104	bhohen@dot.state.tx.us
Texas	Rhonda	Christensen	DOT	512-486-5113	rchris1@dot.state.tx.us
Texas	Cleo	Williams	DOT	512-486-5045	cwilli4@dot.state.tx.us
Utah	Toni	Butterfield	DOT	801-965-4737	tbutterfield@utah.gov
Utah	Todd	Hadden	DOT	???	thadden@utah.gov
Vermont	Bernard	Byrnea	DOT	802-828-2685	bernard.byrnea@state.vt.us
Vermont	Colin	Philbrook	DOT	802-828-3667	colin.philbrook@state.vt.us

Table A1. (Continued) State Department of Transportation vehicle classification contact person information

State	First Name	Last Name	Employer	Work Phone	Email Address
Vermont	John	Blodgett	DOT	802-828-3972	john.blodgett@state.vt.us
Vermont	Carl	Parton	DOT	802-828-6584	carl.parton@state.vt.us
Virginia	Dan	Dunnavant	DOT	804-786-7013	dan.dunnavant@vdot.virginia.gov
Virginia	Richard	Bush	DOT	804-786-0134	richard.bush@vdot.virginia.gov
Virginia	William	Hamlin	DOT	804-786-0134	hamlin.williams@vdot.virginia.gov
Virginia	Dwight	Peters	DOT		dwight.peters@dot.state.ia.us
Washington	John	Rosen	DOT	???	rosenj@wsdot.wa.gov
Washington	Jim	Hawkins	DOT	360-570-2394	hawkins@wsdot.wa.gov
Washington	Tony	Niemi	DOT	360-570-2392	niemit@wsdot.wa.gov
Washington	Kathy	Shelton	DOT	360-570-2397	sheltok@wsdot.wa.dot
West Virginia	Larry	Griffin	DOT	304-558-2864	lgriffith@dot.state.wv.us
West Virginia	Donna	Swigger	DOT	304-558-9620	dswigger@dot.state.wv.us
Wisconsin	John	Williamson	DOT	608-267-2939	John.Williamson@dot.state.wi.us
Wisconsin	Rhonda	McDonald	DOT	608-266-2752	rhonda.mcdonald.dot.state.wi.us
Wyoming	Sherman	Wiseman	DOT	307-777-4190	sherman.wiseman@dot.state.wy.us
Wyoming	David	Clabaugh	DOT	307-777-4185	david.clabaugh@dot.state.wy.us
Wyoming	Kevin	Messman	DOT	307-777-3944	kevin.messman@dot.state.wy.us
Wyoming	Mike	Sanddidge	DOT	???	mike.sandidge@dot.state.wy.us

Table A2. Data collection locations and number of observations per location

Location	Location	Longitude	Latitude	Cross section	ADT (vpd)	Detector type
1	I-94 EB direction near 84th Street	43.02796	-88.00744	3 mainline lanes	77,613	Portable counter & loop detector
2	I-94 EB direction near 35th Street	43.03209	-87.96193	3 mainline lanes + auxiliary right lane	84,762	Portable counter & loop detector
3	I-43 SB near North Avenue	43.05823	-87.92320	3 mainline lanes	73,093	Portable counter & loop detector
4	US 45 NB near North Avenue	43.06729	-88.05338	3 mainline lanes	72,906	Portable counter & loop detector
5	US 45 NB near Wisconsin Avenue	43.03903	-88.03224	3 mainline lanes	89,200	Portable counter & loop detector

Table A3. Vehicle Class Distribution

Vehicle class[a]	Frequency	Percent	Valid Percent	Cumulative Percent
1	20911	.5	.5	.5
2	2852255	71.6	71.6	72.2
3	642631	16.1	16.1	88.3
4	67788	1.7	1.7	90.0
5	108502	2.7	2.7	92.7
6	19559	.5	.5	93.2
7	8468	.2	.2	93.4
8	150391	3.8	3.8	97.2
9	95758	2.4	2.4	99.6
Total	3981810	100.0	100.0	

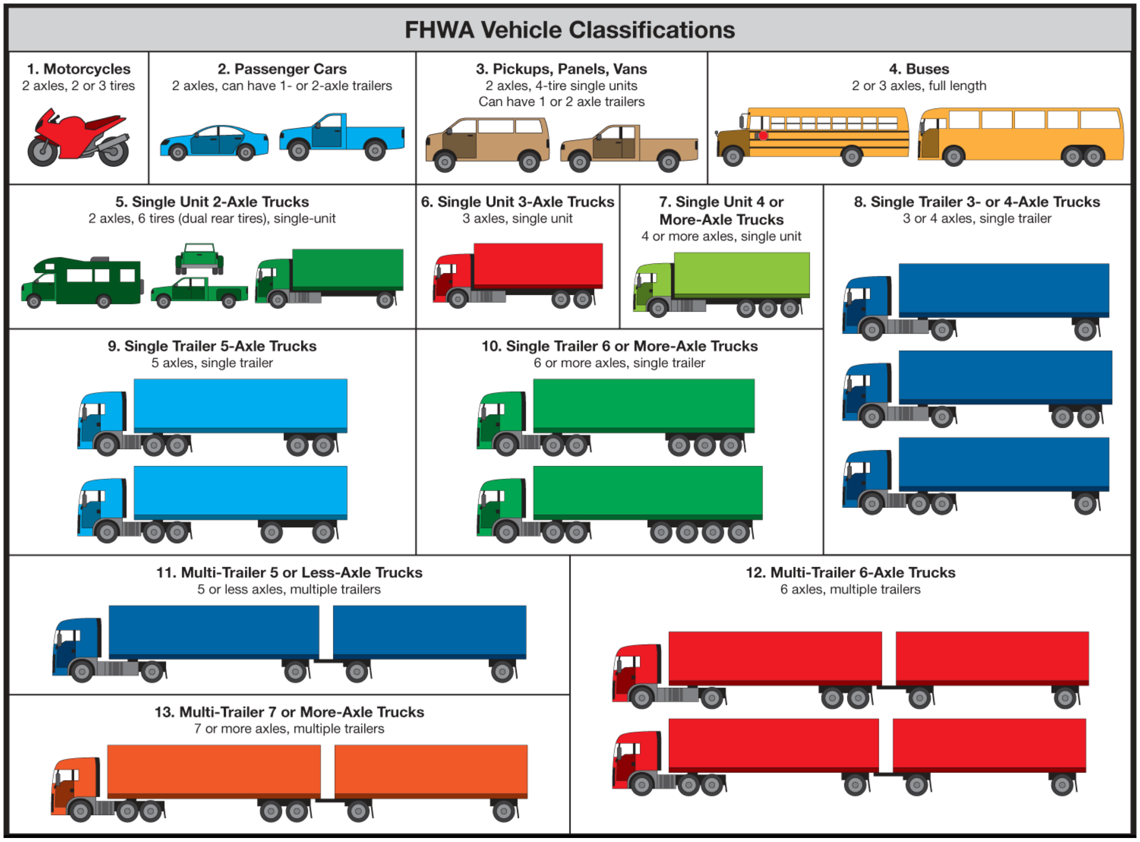
[a] Vehicle Classification Using FHWA 13-Category Scheme—See **Figure A1**.

Note: Vehicles in classes 10-13 constituted 0.4% of the total traffic and are included in the total count.

Table A4. Vehicles within a vehicle class for a given speed range-unfiltered data

Vehicle class	Speed range								
	up to 20 mph	20-25 mph	25-30 mph	30-35 mph	35-40 mph	40-45 mph	45-50 mph	50-55 mph	55+ mph
1	103	153	415	503	812	954	1374	2723	13874
2	10371	15910	28475	41612	49036	61596	113614	345872	2185769
3	3155	3805	7013	10215	11108	13046	24213	74607	495469
4	9464	2317	2168	3499	5618	2984	3561	9102	29075
5	6199	731	1232	1672	1789	2174	4556	13858	76291
6	102	156	257	325	385	463	1032	3506	13333
7	86	118	165	193	218	254	559	2163	4712
8	11808	4768	5215	5162	4692	4903	9354	23686	80803
9	509	817	1328	1736	1553	1869	4610	16038	67298
Total	41797	28775	46268	64917	75211	88243	162873	491555	2966624

Figure A1. Vehicle Classification Using FHWA 13-Category Scheme



Source: http://onlinemanuals.txdot.gov/txdotmanuals/tri/vehicle_classification_using_fhwa_13category_scheme.htm downloaded 6/18/2013

Figure A2. Counter data from US 45 Southbound between Burleigh Street & Wisconsin Avenue

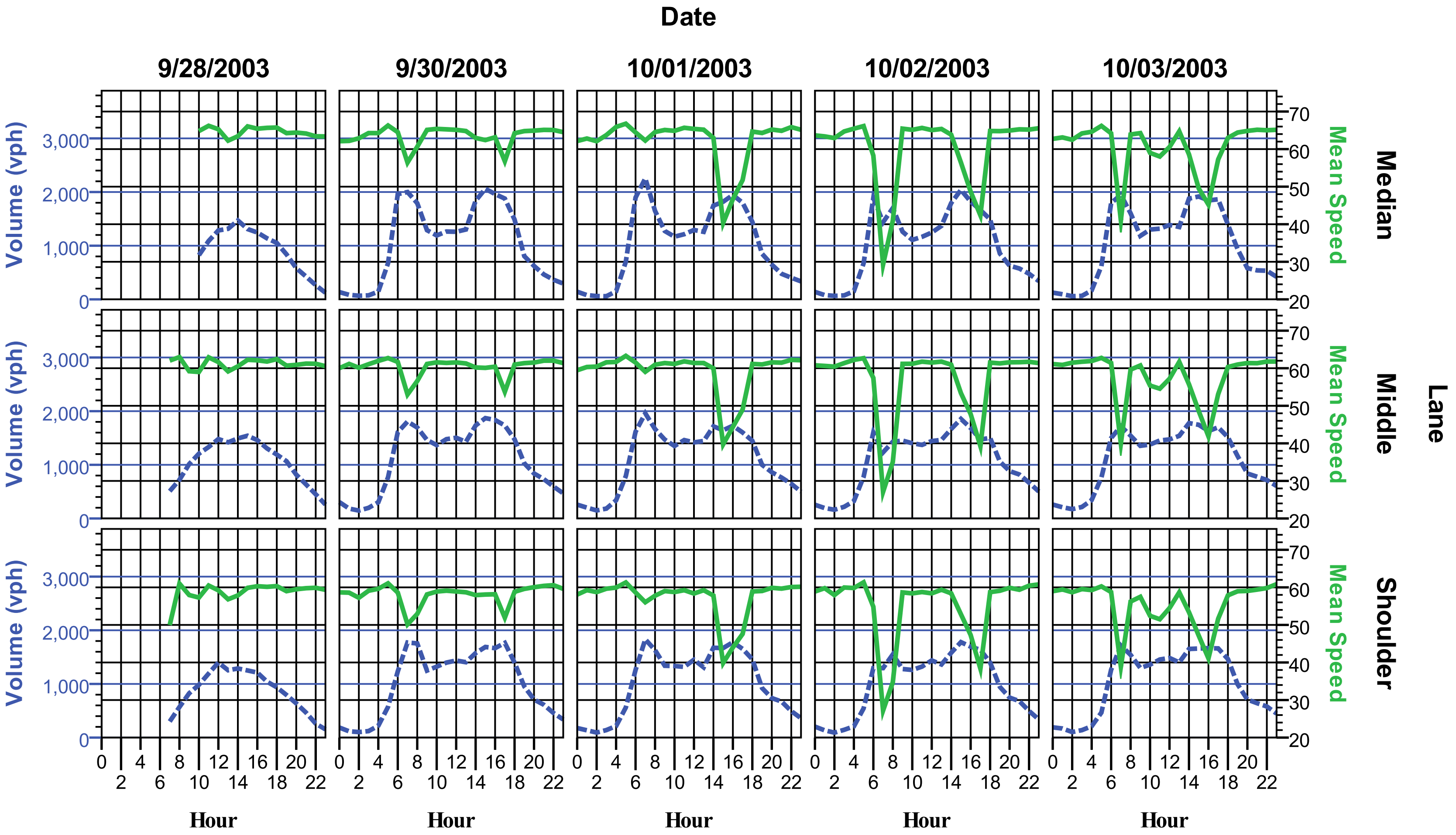


Figure A3. Detector data from US 45 Southbound between Burleigh Street & Wisconsin Avenue

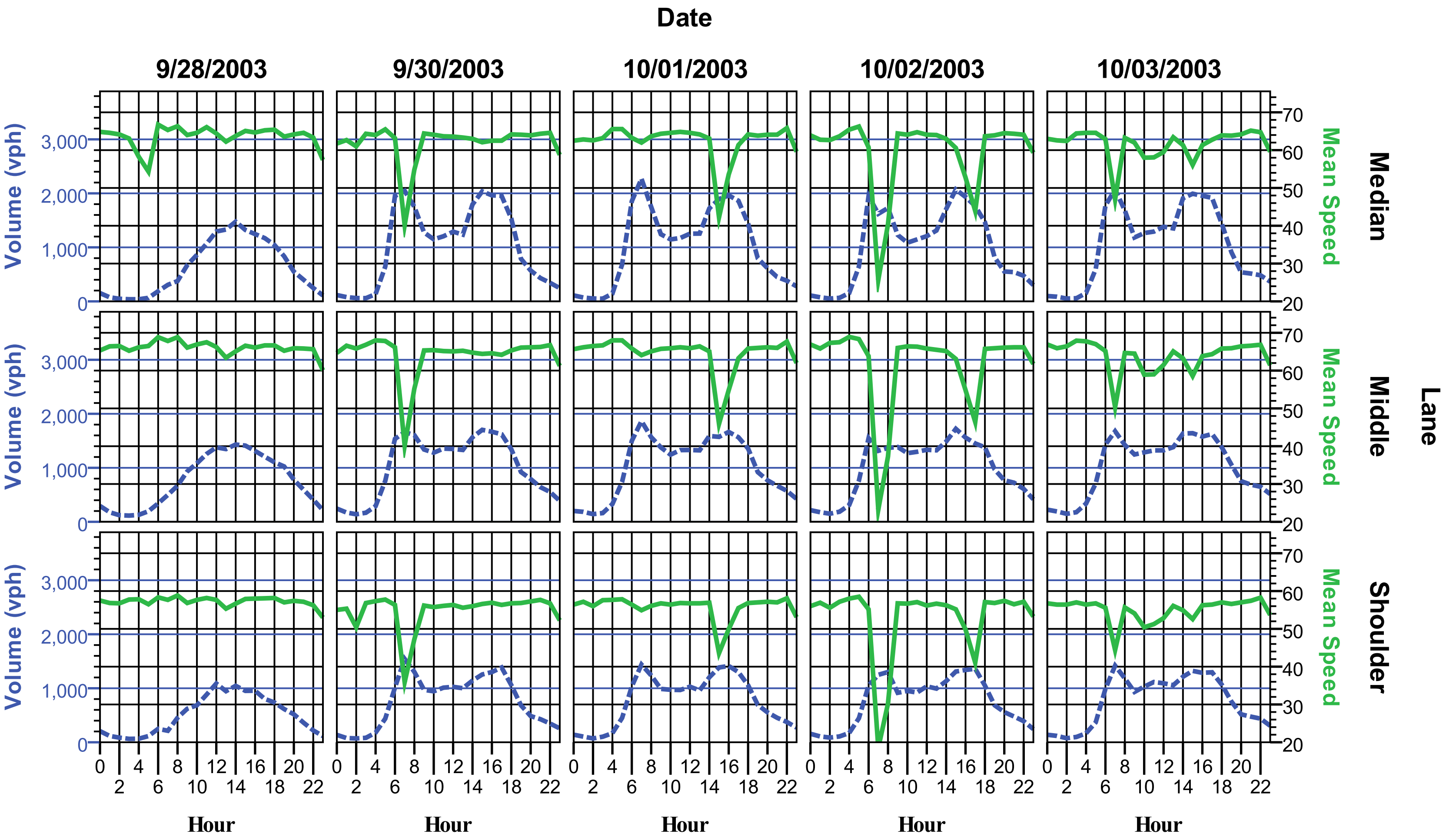
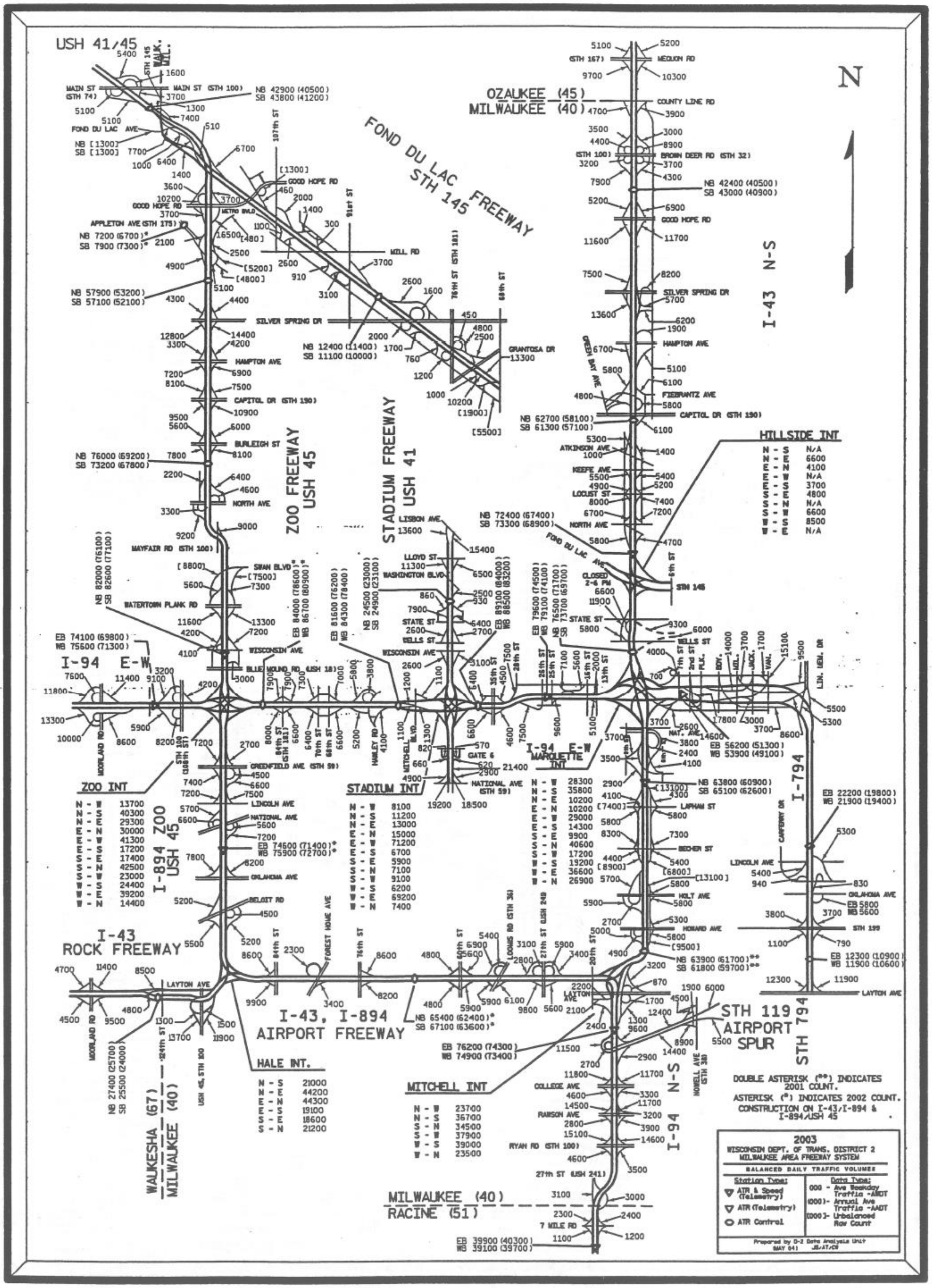


Figure A4. Milwaukee County freeway system traffic counts 2003



Appendix B

Vehicle Pair Types:

Definitions and Headway Statistics

INTRODUCTION

The literature review identified previous efforts that related headways kept between pairs of vehicles in a traffic stream to the vehicle class of each vehicle in a leading/following vehicle pair. The present Appendix focused on the headway analysis of the twelve such leading/following (lead/lag) vehicle pairs defined in **Table B1**.

The objective of the analysis presented herein was to examine headway statistics for each of the twelve lead/lag vehicle pairs defined in **Table B1** in order to:

i. Infer whether certain lead/lag vehicle pair types exhibited indistinguishable headway behavior and therefore could be combined for analysis purposes; and,
ii. Examine headway relations with speed for each lead/lag vehicle pair type.

The statistical analysis for **item i.** above, based on post-hoc multiple comparisons of means using the Bonferroni test statistic indicated that vehicle pair types 202 and 302 (passenger cars following either passenger cars or pick-ups/vans) were not statistically significantly different at any examined speed range. The two vehicle types were therefore merged and are presented under the 202 label in the figures herein. Similarly, vehicle pair types 203 and 303 were merged and are presented under the 203 label in the Figures and Tables of the present Appendix. A listing of the resulting ten lead/lag vehicle pairs can be found in **Table C1**.

Tables and Figures in the present Appendix address **item ii.** above:

Tables B2 through **B10** present findings from the Bonferroni multiple comparisons test providing statistics on differences between the headways of examined lead/lag vehicle pair types one of which is a passenger car and pairs comprising passenger cars following each-other. Statistically significant headway differences are indicated with an asterisk next to the “Mean Difference (I-J)” column. Each table presents findings for one of the nine analyzed speed ranges: Up to 20 mph; 20-25 mph; 25-30 mph; 30-35 mph; 35-40 mph; 40-45 mph; 45-50 mph; 50-55 mph; and 55+ mph
.
Figures B1 through **B9** illustrate average headways and their 95th percentile confidence intervals for each of the analyzed ten lead/lag vehicle pair types; each Figure presents findings for one of the nine analyzed speed ranges listed above.

Table B1. Lead/Lag vehicle pair types

Lead/Lag vehicle pair type[1]	Lead vehicle class[2]	Lag vehicle class[2]
202	Passenger car	Passenger car
203	Passenger car	Pick-up/Van
204	Passenger car	Bus
205	Passenger car	Two-axle single unit truck
208	Passenger car	Four-axle semi-truck
209	Passenger car	Five-axle semi-truck
302[3]	Pick-up/Van	Passenger car
303[3]	Pick-up/Van	Pick-up/Van
402	Bus	Passenger car
502	Two-axle single-unit truck	Passenger car
802	Four-axle semi-truck	Passenger car
902	Five-axle semi-truck	Passenger car

Notes:

[1] Vehicle pair type code 502 indicates a leading vehicle class 5 followed by a vehicle class 2 (see **Figure A1** for vehicle class codes).

[2] Vehicle class is based on the FHWA 13-vehicle class vehicle classification scheme.

[3] 302 was merged with 202 and 303 was merged with 203, based on the Bonferroni multiple comparisons test as explained in the previous page.

Table B2. Speeds up to 20 mph Bonferroni Multiple Comparisons for Headways

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.48113*	.09489	.000	-.7906	-.1717
	204	-1.61252*	.10075	.000	-1.9411	-1.2839
	205	-2.53337*	.10321	.000	-2.8700	-2.1968
	208	-.69108*	.07146	.000	-.9241	-.4580
	209	-1.67445*	.24287	.000	-2.4665	-.8824
	402	-2.57578*	.10397	.000	-2.9149	-2.2367
	502	-.85168*	.22241	.006	-1.5770	-.1263
	802	-2.54246*	.08767	.000	-2.8284	-2.2566
	902	-1.98215*	.24350	.000	-2.7763	-1.1880

*. The mean difference is significant at the 0.05 level.

Table B3. Speeds 20-25 mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.20355*	.02961	.000	-.3001	-.1070
	204	-.66280*	.06464	.000	-.8736	-.4520
	205	-.75206*	.07303	.000	-.9902	-.5139
	208	.00293	.02996	1.000	-.0948	.1006
	209	-1.20180*	.06562	.000	-1.4158	-.9878
	402	-1.29723*	.04514	.000	-1.4444	-1.1500
	502	-.63023*	.06541	.000	-.8435	-.4169
	802	-1.52176*	.03323	.000	-1.6301	-1.4134
	902	-1.20538*	.06437	.000	-1.4153	-.9955

*. The mean difference is significant at the 0.05 level.

Table B4. Speeds 25-30 mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.15449*	.01852	.000	-.2149	-.0941
	204	-.73593*	.05125	.000	-.9031	-.5688
	205	-.52526*	.04591	.000	-.6750	-.3755
	208	-.00161	.02297	1.000	-.0765	.0733
	209	-1.35943*	.04356	.000	-1.5015	-1.2174
	402	-1.18140*	.03848	.000	-1.3069	-1.0559
	502	-.32029*	.04327	.000	-.4614	-.1792
	802	-1.13834*	.02512	.000	-1.2203	-1.0564
	902	-1.06239*	.04572	.000	-1.2115	-.9133

*. The mean difference is significant at the 0.05 level.

Table B5. Speeds 30-35 mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.16183*	.01445	.000	-.2089	-.1147
	204	-.55746*	.03190	.000	-.6615	-.4534
	205	-.44943*	.03696	.000	-.5700	-.3289
	208	-.05746	.02154	.345	-.1277	.0128
	209	-1.19682*	.03576	.000	-1.3134	-1.0802
	402	-.91517*	.03922	.000	-1.0431	-.7873
	502	-.24447*	.03651	.000	-.3635	-.1254
	802	-.92086*	.02316	.000	-.9964	-.8453
	902	-.89997*	.03621	.000	-1.0181	-.7819

*. The mean difference is significant at the 0.05 level.

Table B6. Speeds 35-40 mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.14278*	.01395	.000	-.1883	-.0973
	204	-.67011*	.02314	.000	-.7456	-.5946
	205	-.52558*	.03717	.000	-.6468	-.4044
	208	-.07384	.02265	.050	-.1477	.0000
	209	-1.21716*	.03816	.000	-1.3416	-1.0927
	402	-.68368*	.04120	.000	-.8180	-.5493
	502	-.27463*	.03556	.000	-.3906	-.1587
	802	-.72186*	.02439	.000	-.8014	-.6423
	902	-.74631*	.03816	.000	-.8707	-.6219

*. The mean difference is significant at the 0.05 level.

Table B7. Speeds 40-45 mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.13957*	.01252	.000	-.1804	-.0987
	204	-.90377*	.03342	.000	-1.0127	-.7948
	205	-.55784*	.03275	.000	-.6646	-.4510
	208	-.11159*	.02113	.000	-.1805	-.0427
	209	-1.27550*	.03537	.000	-1.3908	-1.1602
	402	-.60624*	.03872	.000	-.7325	-.4800
	502	-.19438*	.03226	.000	-.2996	-.0892
	802	-.56876*	.02234	.000	-.6416	-.4959
	902	-.65872*	.03479	.000	-.7722	-.5453

*. The mean difference is significant at the 0.05 level.

Table B8. Speeds 45-50 mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.11223*	.01019	.000	-.1455	-.0790
	204	-.91383*	.03436	.000	-1.0259	-.8018
	205	-.50156*	.02522	.000	-.5838	-.4193
	208	-.14705*	.01709	.000	-.2028	-.0913
	209	-1.06437*	.02548	.000	-1.1474	-.9813
	402	-.36126*	.02962	.000	-.4579	-.2647
	502	-.10985*	.02510	.001	-.1917	-.0280
	802	-.41555*	.01857	.000	-.4761	-.3550
	902	-.53204*	.02652	.000	-.6185	-.4456

*. The mean difference is significant at the 0.05 level.

Table B9. Speeds 50-55 mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.09283*	.00656	.000	-.1142	-.0714
	204	-.72653*	.02199	.000	-.7982	-.6548
	205	-.48974*	.01613	.000	-.5423	-.4371
	208	-.20110*	.01216	.000	-.2407	-.1615
	209	-.90937*	.01547	.000	-.9598	-.8589
	402	-.34535*	.01986	.000	-.4101	-.2806
	502	-.09408*	.01643	.000	-.1476	-.0405
	802	-.30951*	.01324	.000	-.3527	-.2663
	902	-.43256*	.01669	.000	-.4870	-.3781

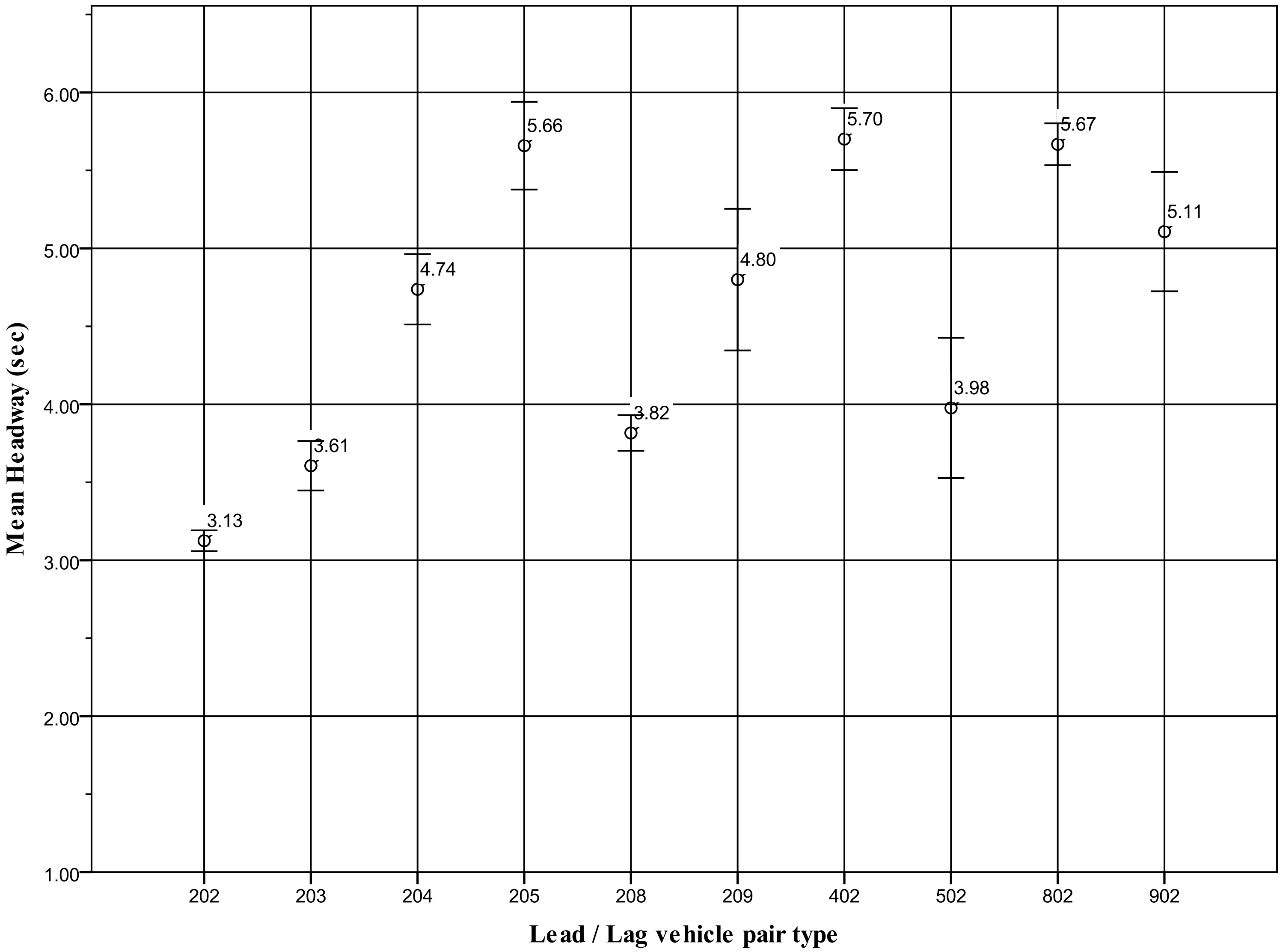
*. The mean difference is significant at the 0.05 level.

Table B10. Speeds 55$^+$ mph Bonferroni Multiple Comparisons for Headways (sec)

(I) Pairs	(J) Pairs	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
202	203	-.04996*	.00302	.000	-.0598	-.0401
	204	-.49419*	.01319	.000	-.5372	-.4512
	205	-.22697*	.00818	.000	-.2536	-.2003
	208	-.17961*	.00727	.000	-.2033	-.1559
	209	-.57789*	.00839	.000	-.6052	-.5505
	402	-.35079*	.01129	.000	-.3876	-.3140
	502	-.09352*	.00802	.000	-.1197	-.0674
	802	-.33587*	.00741	.000	-.3601	-.3117
	902	-.37382*	.00848	.000	-.4015	-.3462

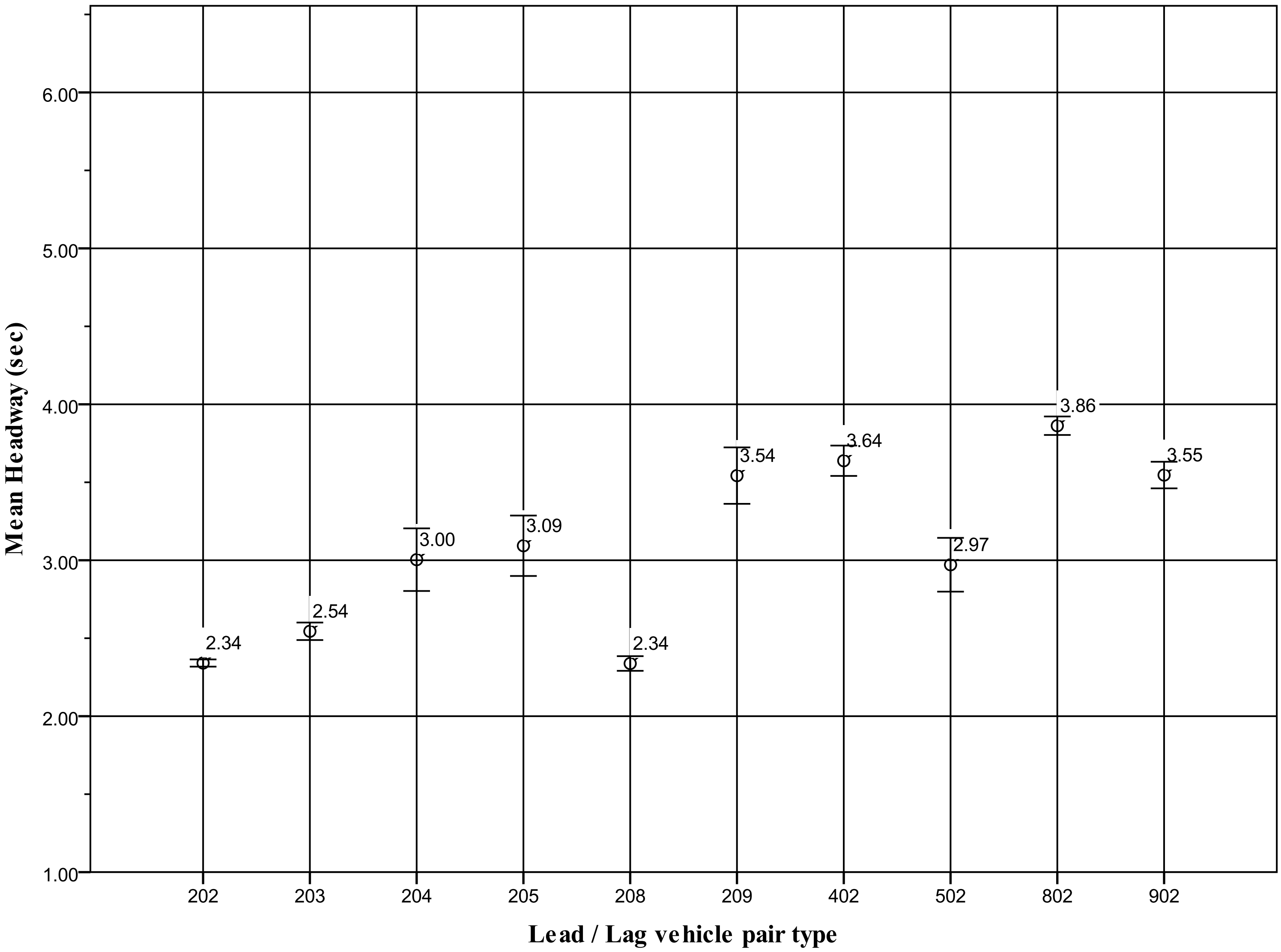
*. The mean difference is significant at the 0.05 level.

Figure B1. 95% Headway CI for speeds up to 20 mph



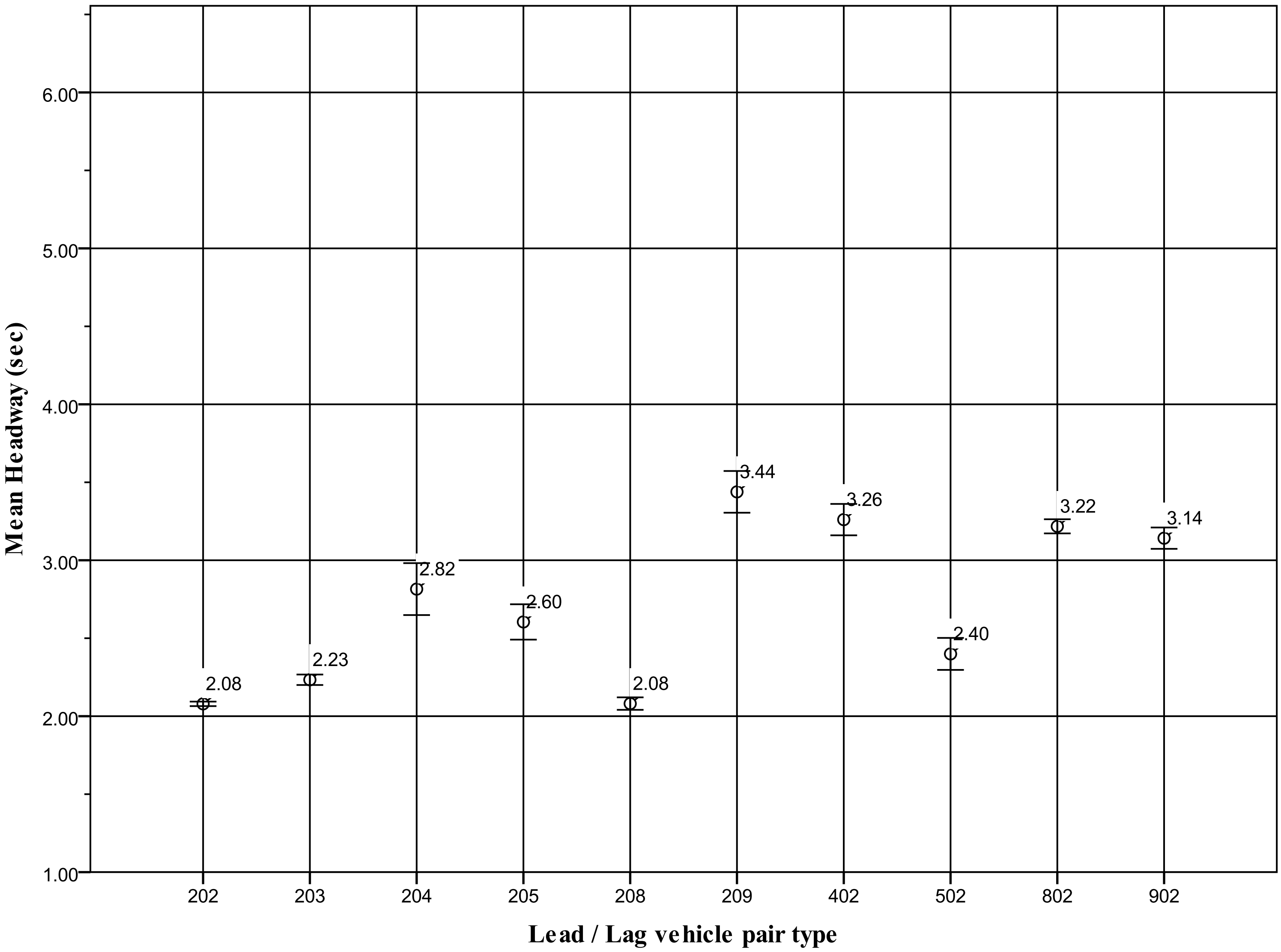
Mean and 95% CI limits

Figure B2. 95% Headway CI for speeds 20-25 mph



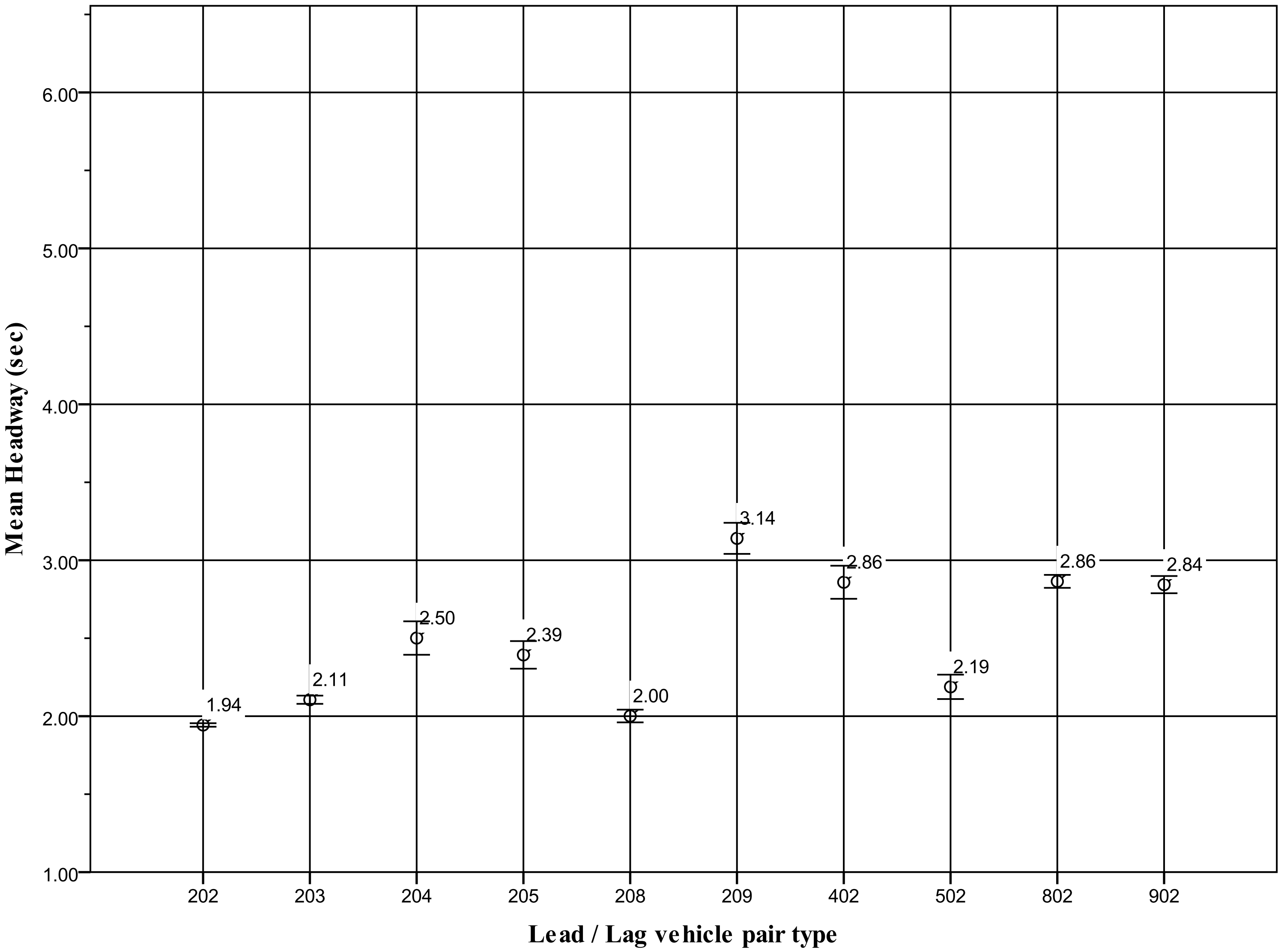
Mean and 95% CI limits

Figure B3. 95% Headway CI for speeds 25-30 mph



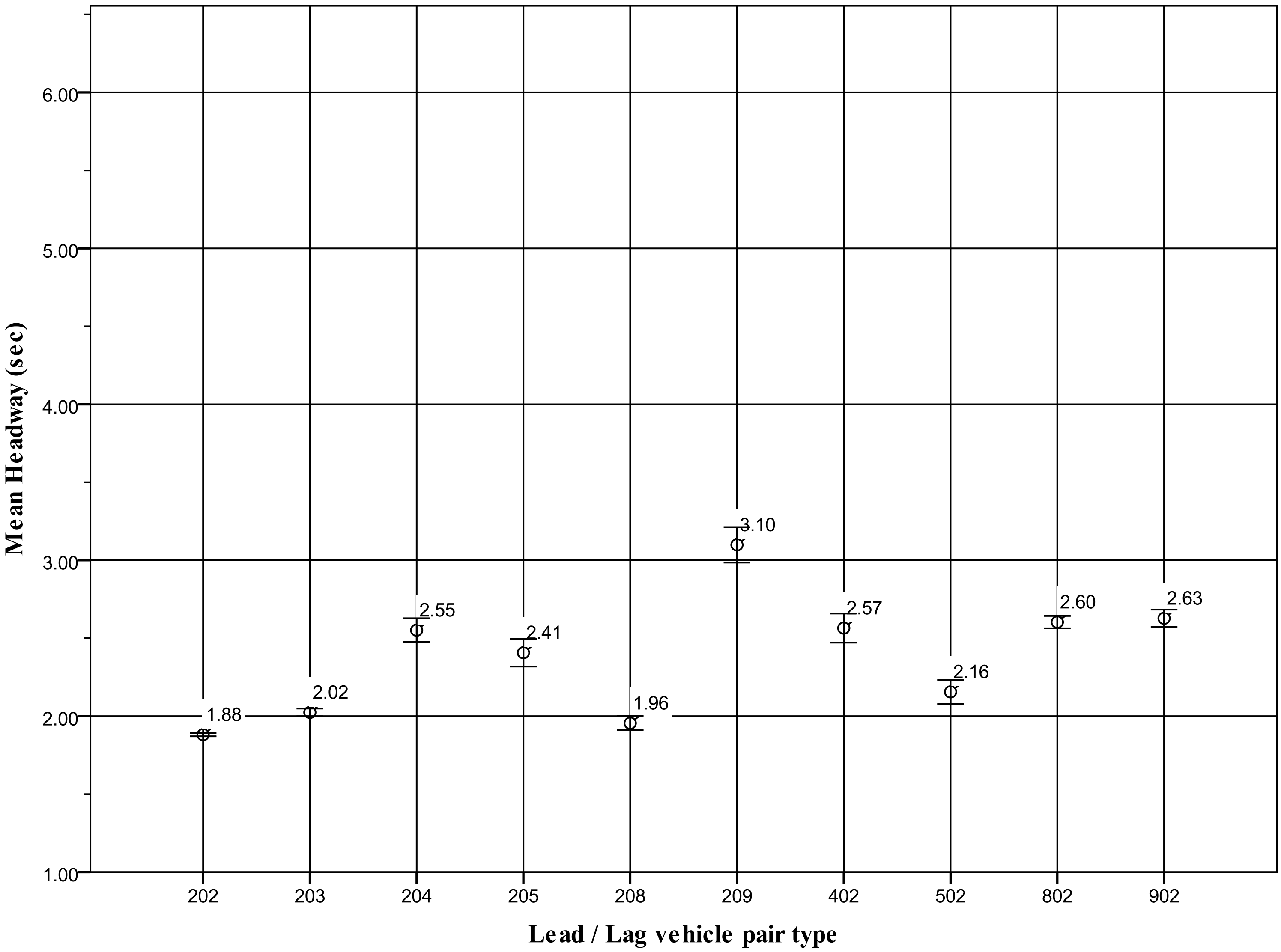
Mean and 95% CI limits

Figure B4. 95% Headway CI for speeds 30-35 mph



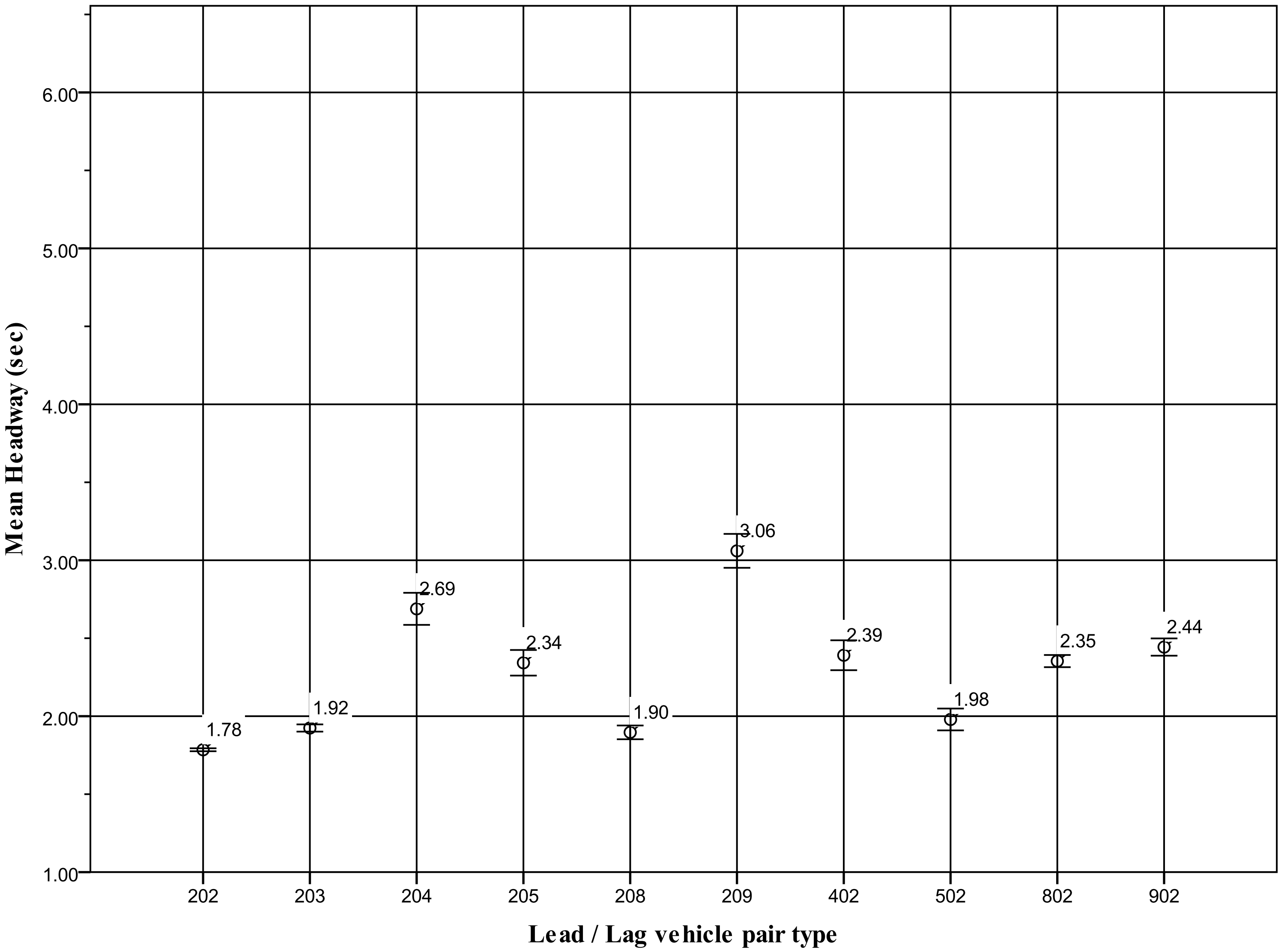
Mean and 95% CI limits

Figure B5. 95% Headway CI for speeds 35-40 mph



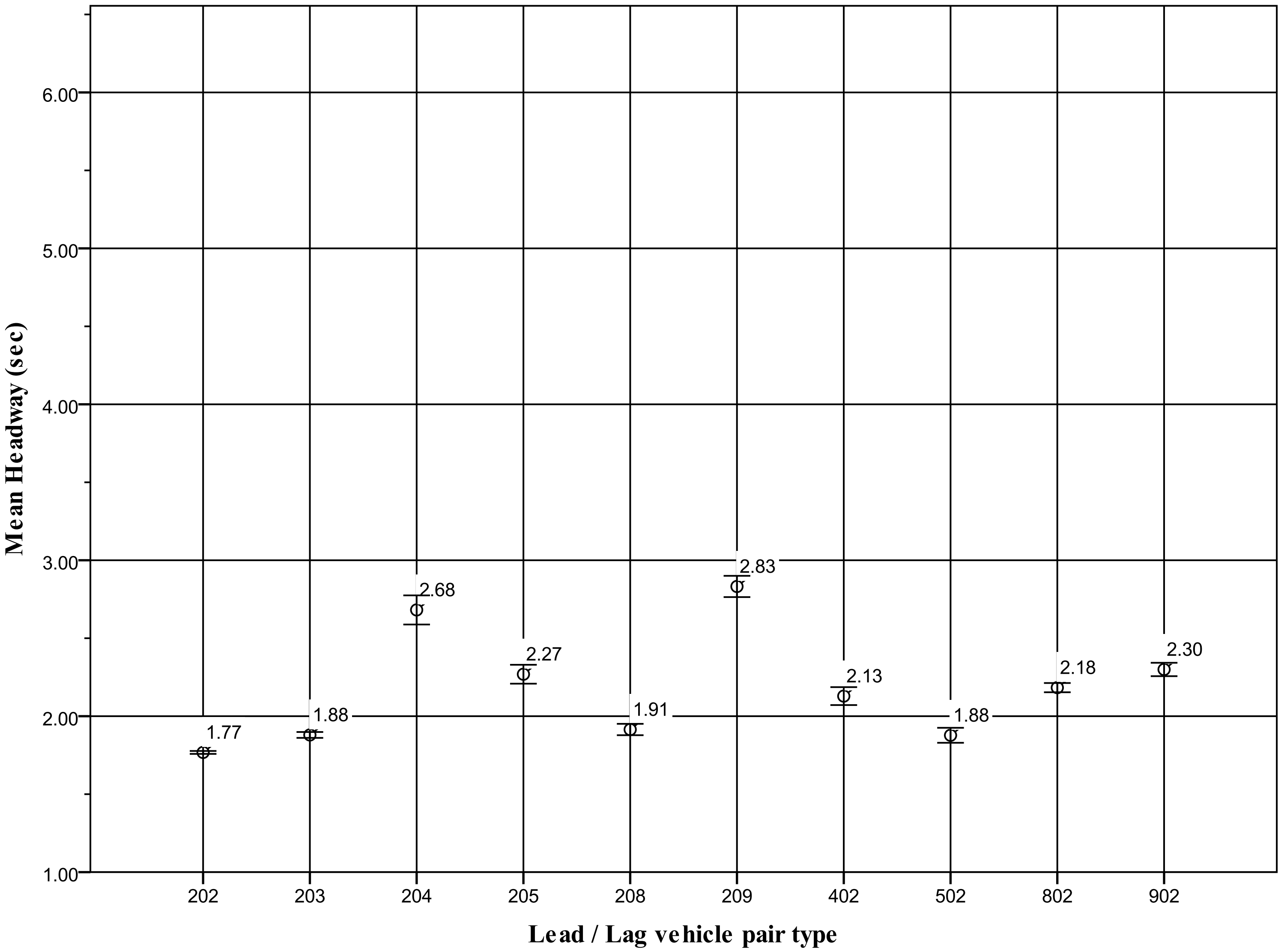
Mean and 95% CI limits

Figure B6. 95% Headway CI for speeds 40-45 mph



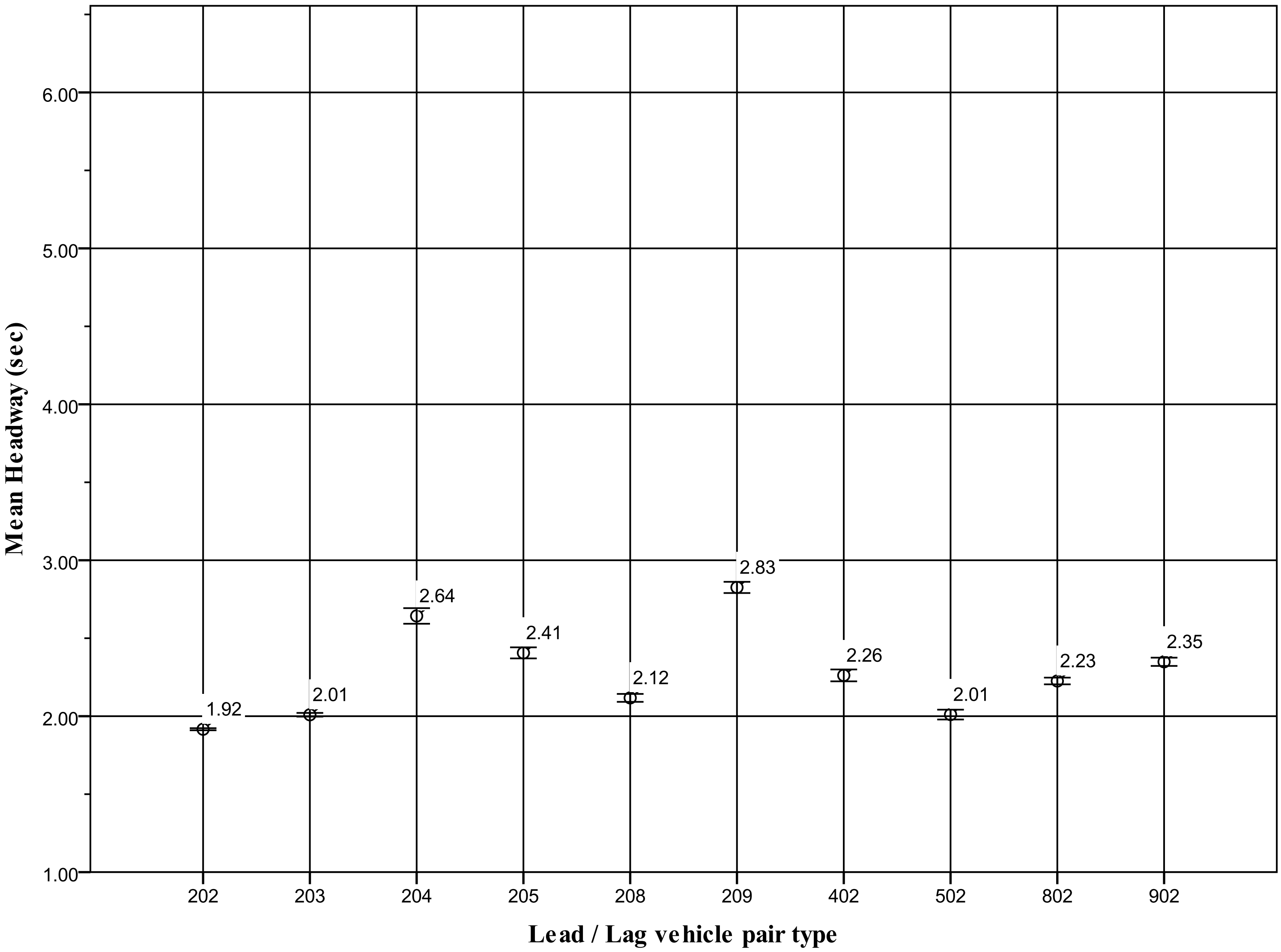
Mean and 95% CI limits

Figure B7. 95% Headway CI for speeds 45-50 mph



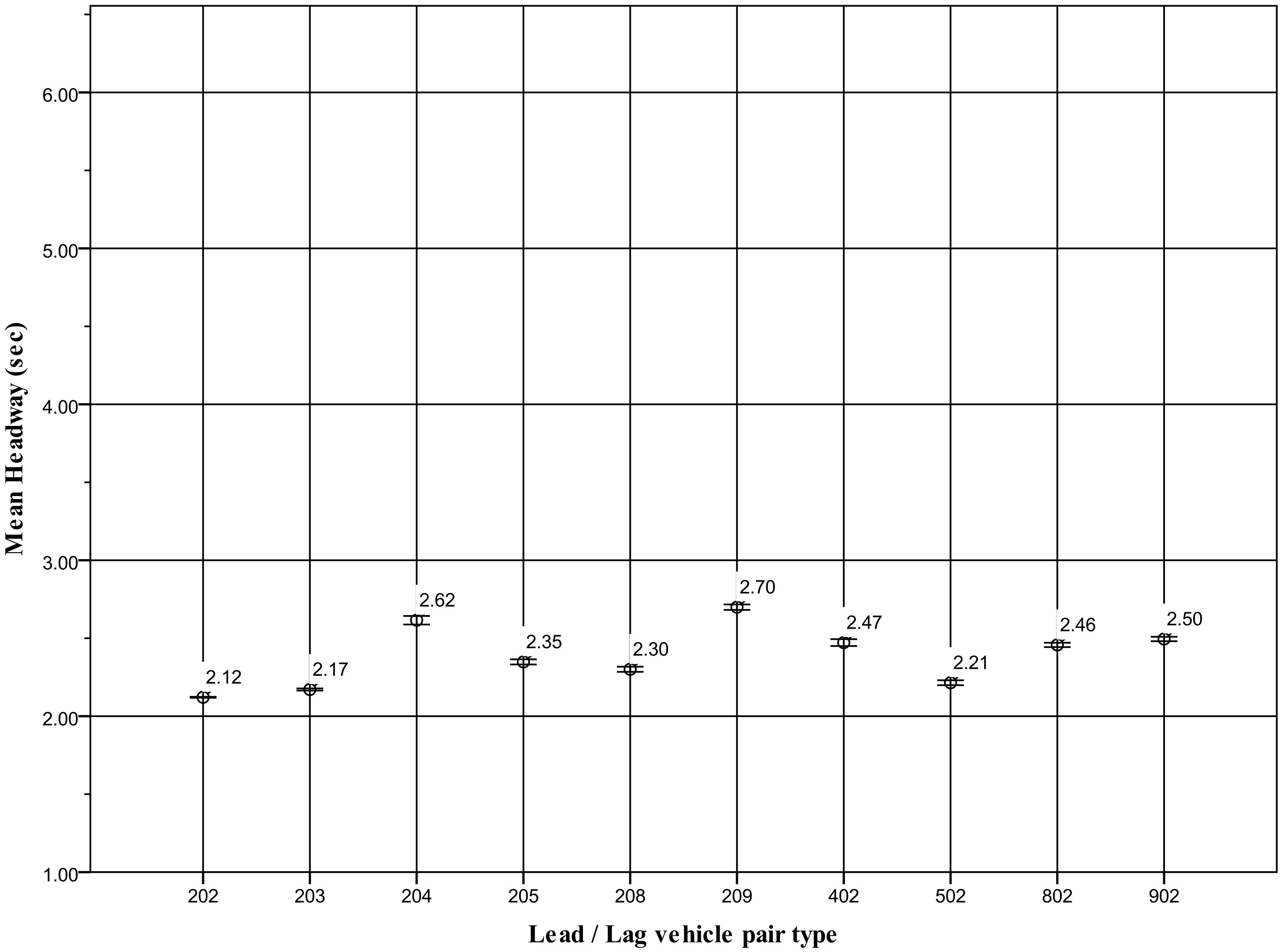
Mean and 95% CI limits

Figure B8. 95% Headway CI for speeds 50-55 mph



Mean and 95% CI limits

Figure B9. 95% Headway CI for speeds 55+ mph



Mean and 95% CI limits

Appendix C

Passenger Car Equivalent calculations

INTRODUCTION

The present Appendix presents headway central tendency statistics (mean, standard deviation, standard error, and 95% confidence interval for the mean) for the ten analyzed lead/lag vehicle pair types presented in **Table C1**. Each of **Tables C2** through **C10** corresponds to one of the nine analyzed speed ranges (Up to 20 mph; 20-25 mph; 25-30 mph; 30-35 mph; 35-40 mph; 40-45 mph; 45-50 mph; 50-55 mph; and 55+ mph). This information was also presented in graphical form in **Figures B1** through **B9**. A summary of average headways for all analyzed speed ranges is presented in **Table C11**.

Average headway information was used to calculate passenger car equivalent values for each of the ten analyzed vehicle pair types presented in **Table C1**. Passenger car equivalent values in **Table C12** were based on the headway ratios described below:

$$PCE_{i,j} = \frac{H_{i,j}}{H_{pc,j}}$$

Where:
$\boldsymbol{i}$ is a specific vehicle type (for example a 2-axle truck)
$\boldsymbol{j}$ is a specific set of physical, traffic and environmental conditions
$\boldsymbol{H_{pc,j}}$ is the mean passenger car headway under conditions j
$\boldsymbol{H_{i,j}}$ is the mean headway for vehicle type i under conditions j
$\boldsymbol{PCE_{i,j}}$ is the passenger car equivalent for vehicle type i under conditions j

Figures C1 and **C2** present average headway information about vehicles (pick-ups/vans, two-axle single-unit trucks and semi-trucks) following passenger cars, in relation to their speed. **Figure C1** focuses on headways; **Figure C2** presents passenger car equivalent information.

Figures C3 and **C4** provide similar information (headway and PCE, respectively) for passenger cars following other vehicles.

Headways for passenger cars following passenger cars is provided to be used as a basis for comparisons in **Figures C1** and **C3**. Passenger car equivalent for passenger cars is equal to 1 for any given speed in **Figures C2** and **C4**.

Figure C5 provides a comparison of headways between situations when a passenger car is being followed versus situations when a passenger follows another vehicle. The comparison is based on the difference ***headway when passenger car is leading minus headway when a passenger car is following another vehicle.*** For example, **Figure C5** shows that his difference is positive for two-axle single-unit trucks, indicating that this heavy vehicle category keeps longer headways when following a passenger car compared to the headways kept by passenger cars when following such vehicles. The difference is positive for the entire analyzed speed spectrum.

Table C1. Lead/Lag vehicle pair types for which PCE values were calculated

Lead/Lag vehicle pair type	Lead vehicle class[a]	Lag vehicle class[a]
202 & 302 [b]	Passenger car or Pick-up/Van	Passenger car
203 & 303 [b]	Passenger car or Pick-up/Van	Pick-up/Van
204	Passenger car	Bus
205	Passenger car	Two-axle single unit truck
208	Passenger car	Four-axle semi-truck
209	Passenger car	Five-axle semi-truck
402	Bus	Passenger car
502	Two-axle single-unit truck	Passenger car
802	Four-axle semi-truck	Passenger car
902	Five-axle semi-truck	Passenger car

Notes:

[a] Vehicle class is based on the FHWA 13-vehicle class vehicle classification scheme.

[b] Vehicle pair 302 was merged with vehicle pair 202 and pair 303 was merged with pair 203, for reasons explained in **page B3**.

Table C2. Speeds up to 20 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	5650	3.1252	2.55390	.03398	3.0586	3.1918
203	1481	3.6063	3.11316	.08090	3.4476	3.7650
204	1276	4.7377	4.11163	.11510	4.5119	4.9635
205	1203	5.6585	4.97281	.14337	5.3772	5.9398
208	3265	3.8162	3.32356	.05816	3.7022	3.9303
209	185	4.7996	3.13048	.23016	4.3455	5.2537
402	1182	5.7009	3.47514	.10108	5.5026	5.8993
502	222	3.9768	3.40207	.22833	3.5269	4.4268
802	1817	5.6676	2.91712	.06843	5.5334	5.8018
902	184	5.1073	2.62881	.19380	4.7249	5.4897
Total	16465	4.1335	3.40652	.02655	4.0814	4.1855

Table C3. Speeds 20-25 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	10937	2.3410	1.23499	.01181	2.3178	2.3641
203	2552	2.5445	1.44491	.02860	2.4884	2.6006
204	452	3.0038	2.17101	.10212	2.8031	3.2045
205	351	3.0930	1.84565	.09851	2.8993	3.2868
208	2479	2.3380	1.19382	.02398	2.2910	2.3851
209	438	3.5428	1.92616	.09204	3.3619	3.7237
402	969	3.6382	1.54427	.04961	3.5408	3.7356
502	441	2.9712	1.84154	.08769	2.7989	3.1435
802	1932	3.8627	1.32935	.03024	3.8034	3.9220
902	456	3.5464	.92668	.04340	3.4611	3.6316
Total	21007	2.6564	1.44840	.00999	2.6368	2.6760

Table C4. Speeds 25-30 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	22123	2.0792	1.10186	.00741	2.0647	2.0937
203	5194	2.2337	1.23325	.01711	2.2002	2.2673
204	563	2.8152	2.01076	.08474	2.6487	2.9816
205	706	2.6045	1.53398	.05773	2.4911	2.7178
208	3117	2.0808	1.14027	.02042	2.0408	2.1209
209	787	3.4387	1.91205	.06816	3.3049	3.5725
402	1019	3.2606	1.63742	.05129	3.1600	3.3613
502	798	2.3995	1.47570	.05224	2.2970	2.5021
802	2548	3.2176	1.16712	.02312	3.1722	3.2629
902	712	3.1416	.92960	.03484	3.0732	3.2100
Total	37567	2.2863	1.26631	.00653	2.2735	2.2991

Table C5. Speeds 30-35 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	34637	1.9438	1.06733	.00573	1.9326	1.9550
203	8036	2.1056	1.20723	.01347	2.0792	2.1320
204	1391	2.5013	2.03903	.05467	2.3940	2.6085
205	1026	2.3932	1.44404	.04508	2.3048	2.4817
208	3204	2.0013	1.17889	.02083	1.9604	2.0421
209	1098	3.1406	1.68207	.05076	3.0410	3.2402
402	908	2.8590	1.62816	.05403	2.7529	2.9650
502	1052	2.1883	1.29229	.03984	2.1101	2.2665
802	2739	2.8647	1.10943	.02120	2.8231	2.9062
902	1070	2.8438	.92021	.02813	2.7886	2.8990
Total	55161	2.0999	1.20562	.00513	2.0898	2.1099

Table C6. Speeds 35-40 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	42052	1.8815	1.08492	.00529	1.8711	1.8919
203	8967	2.0243	1.20450	.01272	1.9994	2.0492
204	2867	2.5516	2.08196	.03888	2.4754	2.6279
205	1067	2.4071	1.47491	.04515	2.3185	2.4957
208	3003	1.9553	1.26025	.02300	1.9103	2.0004
209	1011	3.0987	1.84048	.05788	2.9851	3.2123
402	864	2.5652	1.39608	.04750	2.4720	2.6584
502	1168	2.1561	1.35093	.03953	2.0786	2.2337
802	2564	2.6034	1.03164	.02037	2.5634	2.6433
902	1011	2.6278	.90476	.02846	2.5720	2.6837
Total	64574	2.0167	1.22747	.00483	2.0073	2.0262

Table C7. Speeds 40-45 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	52868	1.7847	1.11279	.00484	1.7753	1.7942
203	10760	1.9243	1.22534	.01181	1.9011	1.9475
204	1285	2.6885	1.87886	.05241	2.5857	2.7913
205	1339	2.3426	1.53039	.04182	2.2605	2.4246
208	3336	1.8963	1.30219	.02255	1.8521	1.9405
209	1144	3.0602	1.87412	.05541	2.9515	3.1690
402	951	2.3910	1.50682	.04886	2.2951	2.4869
502	1381	1.9791	1.32763	.03573	1.9090	2.0492
802	2965	2.3535	1.08443	.01992	2.3144	2.3925
902	1183	2.4435	.97085	.02823	2.3881	2.4988
Total	77212	1.8955	1.20789	.00435	1.8870	1.9040

Table C8. Speeds 45-50 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	93810	1.7676	1.25427	.00410	1.7596	1.7757
203	19542	1.8799	1.33950	.00958	1.8611	1.8987
204	1444	2.6815	1.80962	.04762	2.5881	2.7749
205	2715	2.2692	1.61117	.03092	2.2086	2.3298
208	6121	1.9147	1.45575	.01861	1.8782	1.9512
209	2660	2.8320	1.79214	.03475	2.7639	2.9002
402	1953	2.1289	1.29539	.02931	2.0714	2.1864
502	2742	1.8775	1.28247	.02449	1.8295	1.9255
802	5132	2.1832	1.08461	.01514	2.1535	2.2129
902	2449	2.2997	1.08223	.02187	2.2568	2.3426
Total	138568	1.8618	1.31202	.00352	1.8549	1.8687

Table C9. Speeds 50-55 mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	276609	1.9164	1.42665	.00271	1.9111	1.9217
203	58782	2.0092	1.46638	.00605	1.9973	2.0211
204	4383	2.6429	1.69174	.02555	2.5928	2.6930
205	8254	2.4061	1.64348	.01809	2.3707	2.4416
208	14874	2.1175	1.57870	.01294	2.0921	2.1428
209	9003	2.8257	1.73881	.01833	2.7898	2.8617
402	5390	2.2617	1.42564	.01942	2.2237	2.2998
502	7952	2.0105	1.43463	.01609	1.9789	2.0420
802	12435	2.2259	1.22718	.01100	2.2043	2.2475
902	7697	2.3489	1.18746	.01354	2.3224	2.3755
Total	405379	1.9994	1.45551	.00229	1.9949	2.0039

Table C10. Speeds 55$^+$ mph Headway (sec) descriptive statistics

Lead/Lag vehicle pair type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
202	1305288	2.1213	1.45949	.00128	2.1188	2.1238
203	284539	2.1712	1.46535	.00275	2.1658	2.1766
204	12394	2.6155	1.55415	.01396	2.5881	2.6428
205	32720	2.3482	1.52191	.00841	2.3317	2.3647
208	41754	2.3009	1.53946	.00753	2.2861	2.3156
209	31100	2.6992	1.57232	.00892	2.6817	2.7166
402	16987	2.4721	1.46150	.01121	2.4501	2.4940
502	34077	2.2148	1.48710	.00806	2.1990	2.2306
802	40046	2.4571	1.35680	.00678	2.4439	2.4704
902	30372	2.4951	1.27226	.00730	2.4808	2.5094
Total	1829277	2.1689	1.46604	.00108	2.1668	2.1711

Table C11. Average headways maintained by lead/lag vehicle pair types vs. speed range

Lead/Lag vehicle pair type	Speed range								
	Up to 20 mph	20-25 mph	25-30 mph	30-35 mph	35-40 mph	40-45 mph	45-50 mph	50-55 mph	55+ mph
202	3.13	2.34	2.08	1.94	1.88	1.78	1.77	1.92	2.12
203	3.61	2.54	2.23	2.11	2.02	1.92	1.88	2.01	2.17
204	4.74	3.00	2.82	2.50	2.55	2.69	2.68	2.64	2.62
205	5.66	3.09	2.60	2.39	2.41	2.34	2.27	2.41	2.35
208	3.82	2.34	2.08	2.00	1.96	1.90	1.91	2.12	2.30
209	4.80	3.54	3.44	3.14	3.10	3.06	2.83	2.83	2.70
402	5.70	3.64	3.26	2.86	2.57	2.39	2.13	2.26	2.47
502	3.98	2.97	2.40	2.19	2.16	1.98	1.88	2.01	2.21
802	5.67	3.86	3.22	2.86	2.60	2.35	2.18	2.23	2.46
902	5.11	3.55	3.14	2.84	2.63	2.44	2.30	2.35	2.50

Table C12. Passenger car equivalents for lead/lag vehicle pair types vs. speed range

Lead/Lag vehicle pair type	Speed range								
	Up to 20 mph	20-25 mph	25-30 mph	30-35 mph	35-40 mph	40-45 mph	45-50 mph	50-55 mph	55+ mph
202	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
203	1.154	1.087	1.074	1.083	1.076	1.078	1.063	1.048	1.024
204	1.516	1.283	1.354	1.287	1.356	1.506	1.517	1.379	1.233
205	1.811	1.321	1.253	1.231	1.279	1.313	1.284	1.256	1.107
208	1.221	.999	1.001	1.030	1.039	1.063	1.083	1.105	1.085
209	1.536	1.513	1.654	1.616	1.647	1.715	1.602	1.475	1.272
402	1.824	1.554	1.568	1.471	1.363	1.340	1.204	1.180	1.165
502	1.273	1.269	1.154	1.126	1.146	1.109	1.062	1.049	1.044
802	1.814	1.650	1.547	1.474	1.384	1.319	1.235	1.162	1.158
902	1.634	1.515	1.511	1.463	1.397	1.369	1.301	1.226	1.176

Figure C1. Headways for heavy vehicles following passenger cars vs. speed range

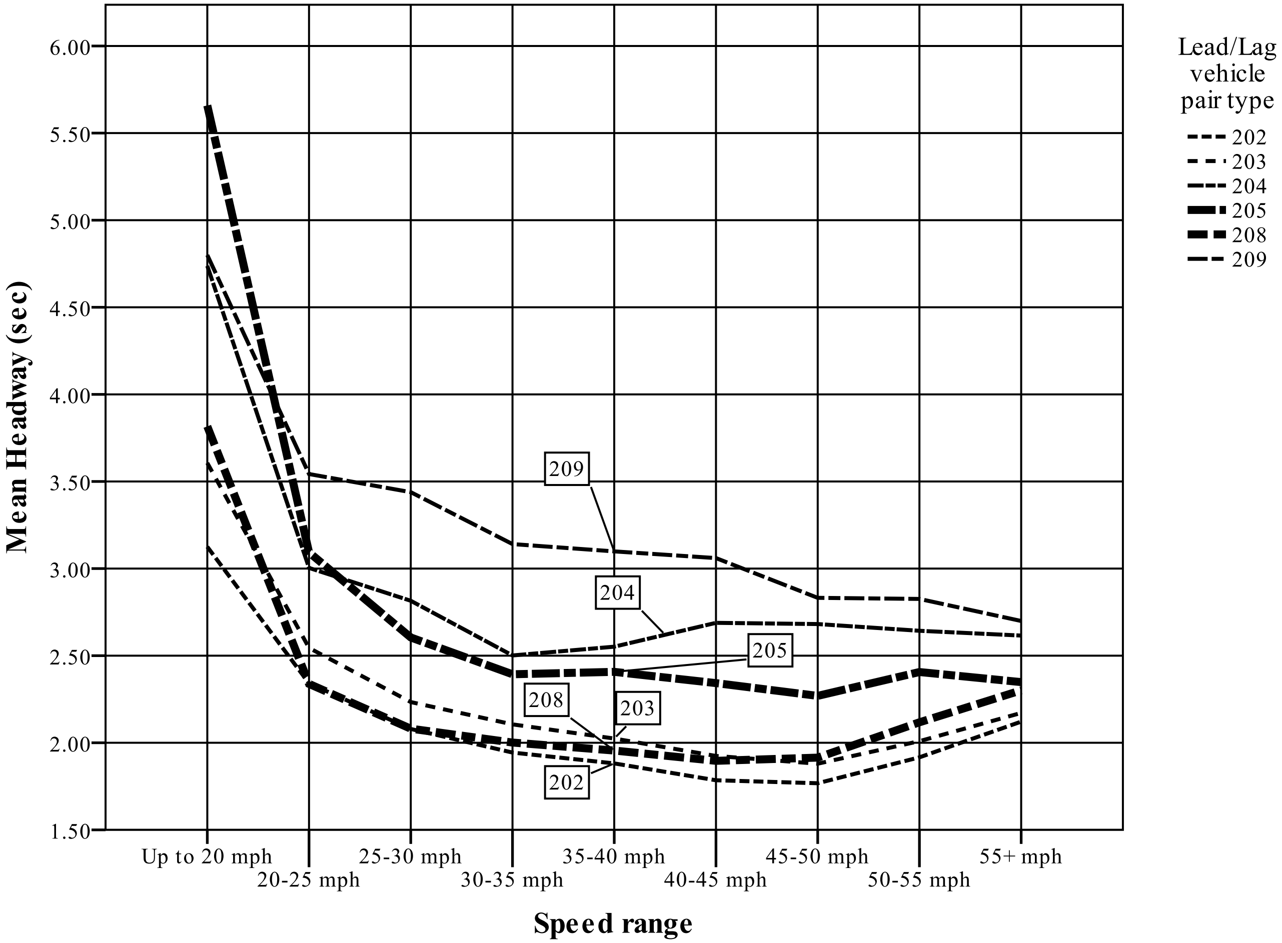


Figure C2. Passenger Car Equivalents for heavy vehicles following passenger cars vs. speed range

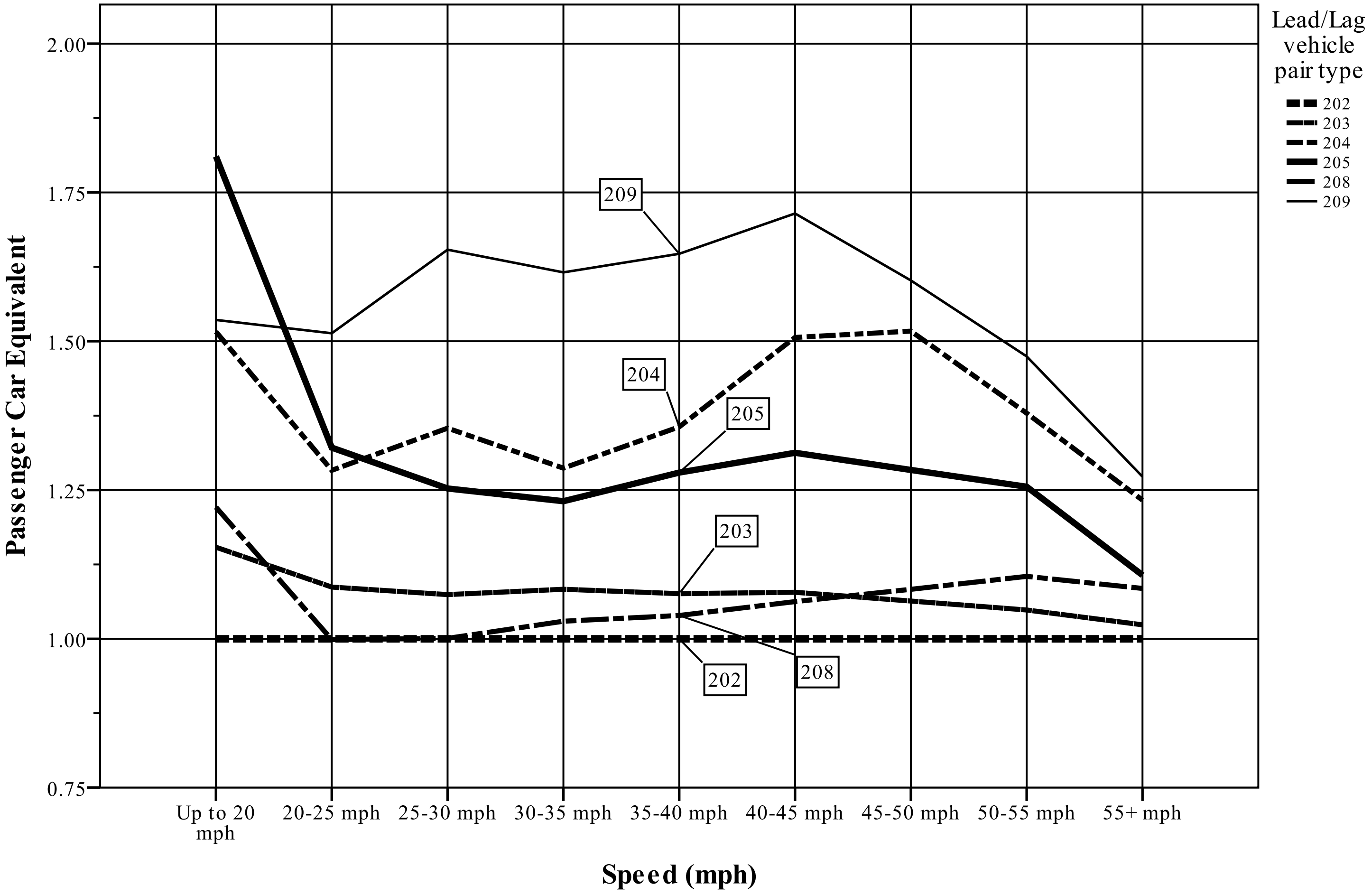


Figure C3. Headways for passenger cars following heavy vehicles vs. speed range

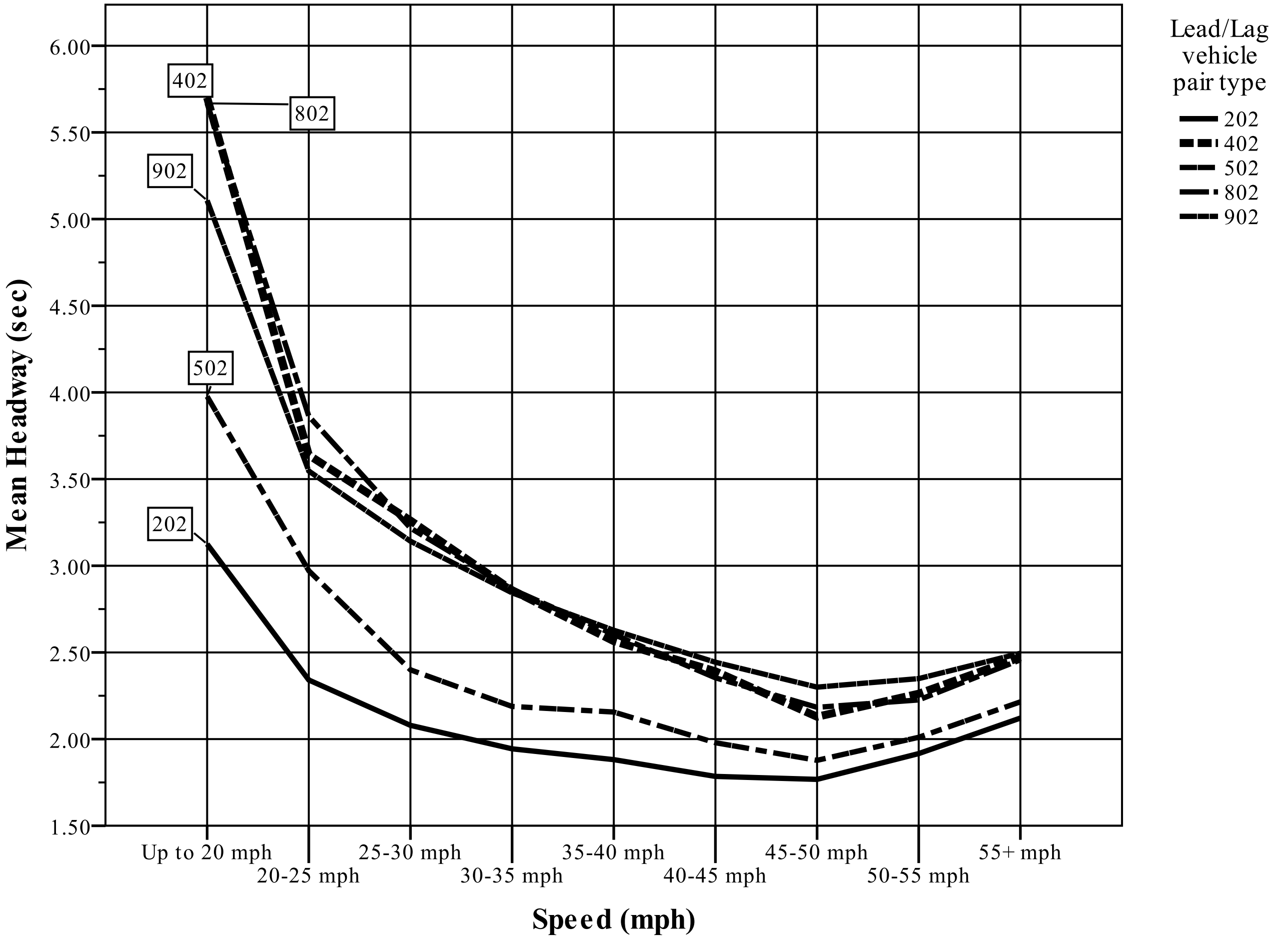


Figure C4. Passenger Car Equivalents for passenger cars following heavy vehicles vs. speed

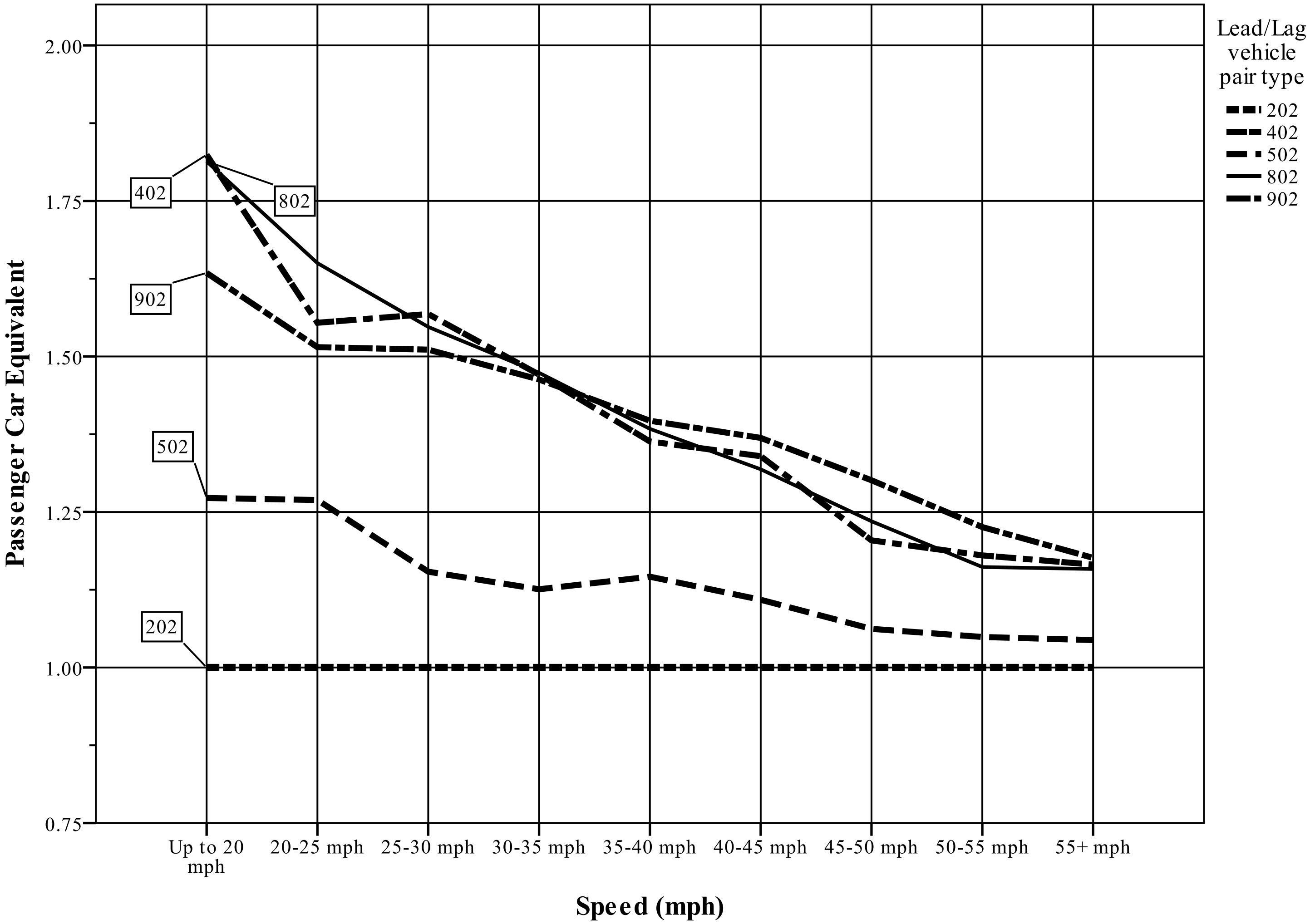
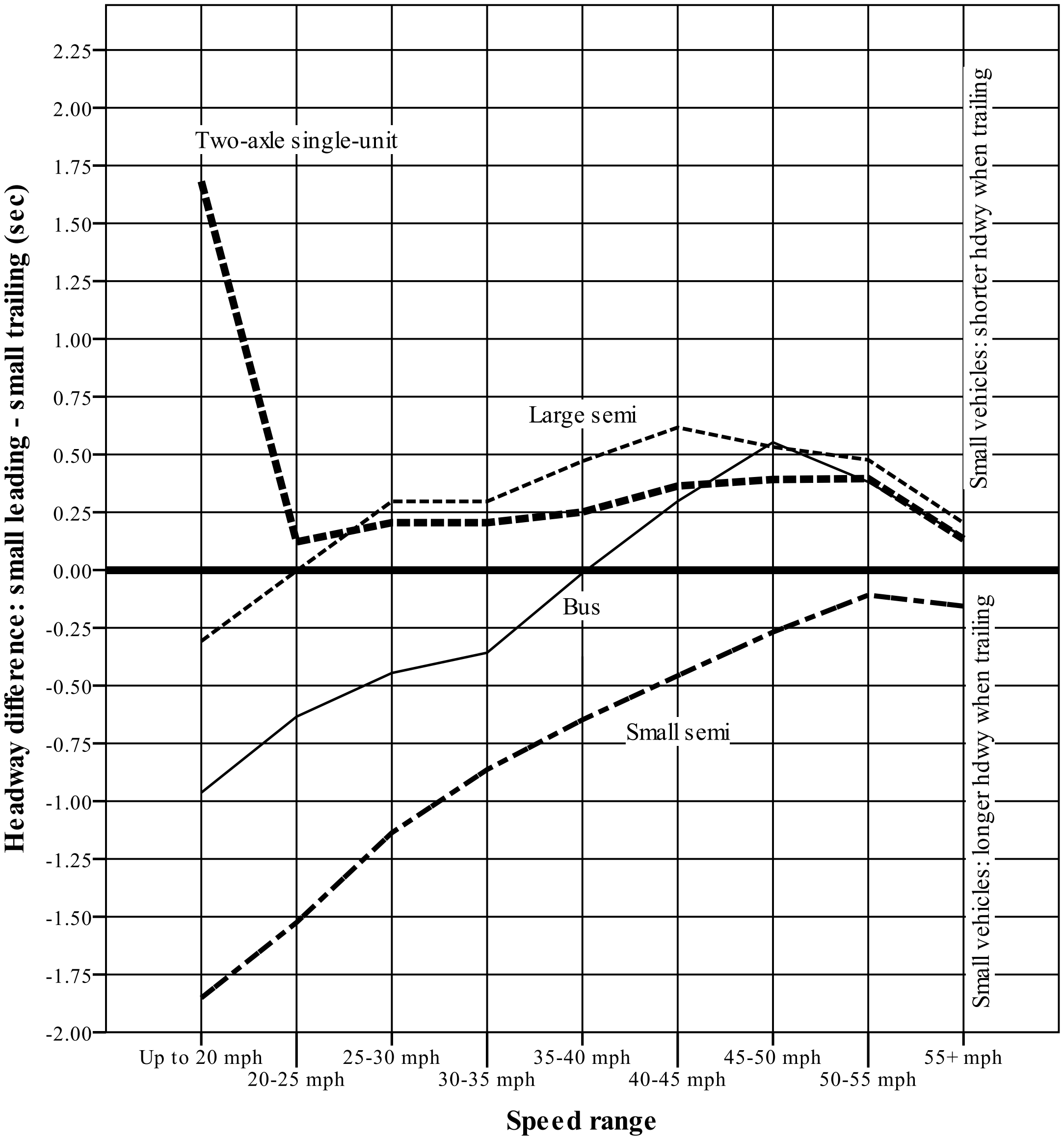


Figure C5. Headway differences for small vehicles leading vs. following large vehicles



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