TRAFFIC PERFORMANCE ON TWO-LANE, TWO-WAY HIGHWAYS:

EXAMINATION OF NEW ANALYTICAL APPROACHES

by

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ABSTRACT

This project presents research on estimating traffic performance on two-lane, two-way highways. The main research objective is to examine two new approaches / methodologies in estimating the Percent-Time-Spent-Following (PTSF), a major indicator of performance on two-lane highways. The first new approach, named the weighted-average approach, is based on the weighted average of speeds for various vehicle types within the traffic stream. The second new approach, named the probabilistic approach, is concerned with using probabilities in estimating the PTSF.

The need for this investigation has arisen from the concern that the current analytical procedures, namely the Highway Capacity Manual (HCM) 2000, provide erroneous results as suggested by previous research. The project reviews recent literature on the HCM procedures and evaluates their effectiveness using both theoretical and empirical analyses. Furthermore, the two new approaches were evaluated using empirical data from three study sites located throughout Montana's two-lane, two-way highway system.

CHAPTER 1

INTRODUCTION

General Overview

Two-lane, two-way highways are a key element in the highway system of most countries, where they provide a variety of transportation related functions, are located in all geographic areas, and serve a wide range of vehicle traffic (TRB 2000). Figure 1 shows a typical view of a two-lane, two-way rural highway.

Figure 1 Typical Two-Lane, Two-Way Highway (Picture Courtesy of FHWA)

Two-lane, two-way highways comprise the vast majority of highway facilities in areas where the bulk of vehicular travel takes place in rural settings. In the United States, two-lane, two-way highways constitute more than 82% of the National highway system as measured by length in miles. This corresponds to 64% in urban areas and 90% in rural areas excluding highways in Federal parks, forests, and reservations that are not part of the State and local highway systems (FHWA 2003).

Traffic operations on two-lane, two-way highways differ from other facilities due to the unique relationship between traffic conditions in the two directions of travel. In particular, lane changing and passing maneuvers are restricted on two-lane, two-way highways and are typically performed using the opposing lane of travel when sight distance and more importantly gaps in the opposing traffic stream permit. For this reason, on two-lane, two-way highways, normal traffic flow in one direction influences flow in the other direction. Consequently, two-lane, two-way highways are known for their higher level of interaction between vehicles in the opposing directions of travel and therefore provide unique challenges to traffic analysts.

This frequent interaction between vehicles in opposing lanes of travel has significant connotations on traffic performance in that the restricted passing opportunities heighten the impact of slow-moving vehicles (mainly trucks, agricultural vehicles, and low performance vehicles) on traffic mobility and facility performance. This impact generally intensifies with the increase in traffic level in the two directions of travel, the proportion of slower vehicles in the traffic stream, and the average speed differential between slower vehicles and the rest of the driver population (Al-Kaisy and Durbin

2005). Consequently, analysts face a tremendous challenge in developing a process capable of capturing facility performance on two-lane, two-way highways.

The analysis of traffic performance on two-lane two-way highways is essential for the planning, design, and operation of those facilities. It is a major input to important decisions on public fund investments that are made at different stages of the highway life. Performance analysis is typically done within the capacity analysis for various highway facilities. The National document that outlines the capacity analysis procedures is the Highway Capacity Manual (HCM) published by the Transportation Research Board (TRB 2000). Using these procedures, performance is typically described using Level Of Service (LOS), which is a letter scheme intended to describe traffic conditions for an existing or proposed facility operating under current or projected traffic demand. Currently, two analytical tools are used at the national level to analyze the performance of two lane highways 1) the previously mentioned HCM analytical procedures, and 2) the microscopic traffic simulation model TWOPAS that is used occasionally to complement the HCM procedures.

The HCM utilizes two performance measures on two-lane, two-way highways: Percent Time-Spent-Following (PTSF) and Average Travel Speed (ATS). PTSF refers to the percentage of travel time a vehicle is trapped in a platoon on a two-lane highway being unable to pass slower vehicles (TRB 2000). Average travel speed is the length of highway divided by the average travel time of vehicles on the segment and is considered to be a reflection of the mobility on a two-lane highway (TRB 2000).

TWOPAS is regarded as the main simulation model for two-lane, two-way highways and was used extensively in the development of the HCM 2000 two-lane highway analysis procedures (Harwood et al. 1999). Furthermore, TWOPAS is the traffic analysis module for a collection of software analysis tools for evaluating safety and operational effects of geometric design decisions on two-lane, two-way rural highways known as the Interactive Highway Safety Design Model (IHSDM) (USDOT, 2005).

Problem Statement

While the concept of the PTSF is sound, it is difficult or impractical to measure in the field. For this reason, the current HCM procedures suggest a surrogate measure in estimating the PTSF in the field, that is; the percentage of vehicles traveling with headways of less than three seconds. A headway is the "time, in seconds, 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)" (TRB, 2000). Recent studies (Dixon et al. 2002; Luttinen 2000 and 2002) revealed inconsistency between the analytical procedures included in the HCM and field measurement as concerned with the estimation of the PTSF. Specifically, PTSF values found from the models included in the HCM or from TWOPAS were significantly overestimated when compared to their counterparts from field measurements. Furthermore, the HCM procedures fail to provide a logical connection between the PTSF and the platooning phenomenon on two lane highways which is a major determinant of the PTSF.

Objective/Scope

The main objective of this research is to examine two new concepts / methodologies in estimating the PTSF. The first new concept, named the weighted average approach, is based on the weighted average of speeds for various vehicle types within the traffic stream. The second new concept, named the probabilistic approach, is concerned with using probabilities in estimating PTSF. Also, this research examines the current HCM procedures for the analysis of two-lane highways.

Two-lane, two-way highways appear in rural, suburban, or urban settings and have a variety of operational characteristics. In this regard, this research is mainly concerned with those highways that exist in rural or suburban settings where traffic interruptions are of low intensity. Also, capacity of two-lane highways is considered beyond the scope of this research.

Thesis Organization

Following this chapter, Chapter 2 provides a review of the current literature in regard to two-lane, two-way highways and their operational characteristics. Specifically, the chapter discusses the two-lane highways, the current analytical procedures, and the limitations of these procedures as reported in the literature.

Chapter 3 examines the HCM 2000 procedures for two lane highways using theoretical and empirical analyses. In particular, theories on car-following and headway distributions as well as empirical headway distribution were used in these analyses.

Chapter 4 describes the two new concepts for estimating the performance measure PTSF; the weighted-average approach and the probabilistic approaches. The concept of the two approaches is based on the premise that vehicles in a platoon on two-lane highways may voluntarily or involuntarily travel at the platoon speed.

Chapter 5 discusses the field data collection and processing including the selection of study sites, description of study sites, and description of the data used in this research. Chapters 6-8 include the proof-of-concept of the two proposed approaches using empirical data. Chapter 6 examines the platooning phenomenon on two lane highways as related to the new proposed approaches, while chapters 7 and 8 examines the two proposed approaches for estimating the PTSF using field data. The sensitivity of the PTSF estimation to important traffic parameters are examined and evaluated.

Chapter 9 provides a comparison of the PTSF estimation using results from the two new methods, the current HCM PTSF models, and the HCM field measurement procedure using data from study sites. Finally, the most important findings of the current research along with recommendations for future research are presented in Chapter 10 of the thesis.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses the current literature concerning the definition of two-lane, two-way highways and their operational characteristics. The chapter also provides discussion on measuring performance on two-lane, two-way highways. The chapter concludes with an overview of some of the limitations of the procedures for measuring performance on two-lane, two-way highways, as documented in current literature.

Defining Two-Lane, Two-Way Highways

"The decision to provide a 2-lane highway many times is not justified on demand and capacity requirements alone, therefore, but on minimum level of service requirements which justify at least one travel lane in each direction for safety, convenience, and tolerable operating conditions" (HRB 1965). This brief description for what justifies the implementation of two-lane, two-way highways shows that level-of-service (LOS) is a very important parameter for assessing the performance of two-lane, two-way highways.

Equally important is the need for accurate performance measures used to establish the LOS, which is defined in detail later in this chapter. As Luttinen stated, performance measures are quantitative descriptions of traffic flow quality. A good performance measure describes the perceptions of the traffic facilities users and is useful for traffic engineers analyzing the facilities (Luttinen, 2000).

Definition and Operational Characteristics

Two-lane, two-way highways are defined in the Highway Capacity Manual (HCM) as undivided roadway with two lanes, one for use by traffic in each direction and are classified as either (TRB 2000):

1. Class I – These are two-lane, two-way highways on which motorists expect to travel at relatively high speeds. Two-lane, two-way highways that are major intercity routes, primary arterials connecting major traffic generators, daily commuter routes, or primary links in state or national highway networks generally are assigned to Class I. Class I facilities most often serve long-distance trips or provide connecting links between facilities that serve long-distance trips.
2. Class II – These are two-lane, two-way highways on which motorists do not necessarily expect to travel at high speeds. Two-lane, two-way highways that function as access routes to Class I facilities, serve as scenic or recreational routes that are not primary arterials, or pass through rugged terrain generally are assigned to Class II. Class II facilities most often serve relatively short trips, the beginning and ending portions of longer trips, or trips for which sightseeing plays a significant role.

It is important to note that the classification of two-lane, two-way highways is based more on motorist expectation rather than highway functionality. For example, a highway connecting two major cities that passes over a rugged mountain pass could be classified as Class II rather than Class I if motorists feel that high speeds are not feasible on the corridor.

To further classify two-lane, two-way highways, they are highway facilities that function under uninterrupted-flow, where operations are largely based on interactions between vehicles moving in the same as well as in opposing directions. An uninterrupted-flow facility as defined by the HCM 2000 is "a category of facilities that have no fixed causes of delay or interruption external to the traffic system; examples include freeways and unsignalized sections of multilane and two-lane rural highways" (TRB, 2000). Pure uninterrupted flow exists primarily on freeways, where traffic is free to travel without hindrance from external interruptions, such as: 1) intersections at grade, 2) driveways, 3) other forms of direct access to adjoining lands, 4) traffic signals, 5) STOP or YIELD signs, and 6) other interruptions external to the traffic stream.

Furthermore, as the HCM states (TRB 2000), traffic operations on two-lane, two-way highways are differentiated from the other uninterrupted-flow facilities by the following:

1. lane changing and passing are possible using only the opposing lane of travel,
2. passing demand increases rapidly as traffic volumes increase, and
3. passing capacity in the opposing lane declines as volumes increase.

From the above characteristics, it can be seen that, unlike other uninterrupted-flow facilities, normal traffic flow in one direction influences flow in the other direction on two-lane, two-way highways. "On a two-lane, two-way road, vehicles must, to overtake and pass vehicles traveling in the same direction, use the lane normally used by oncoming traffic" (HRB 1950). As many two-lane, two-way highways connect major traffic generators (i.e. universities, arenas, malls, etc.) they need to provide safe and timely travel. According to Polus et al. (1999), roadway capacity, safety, and level of service are all affected by the passing ability of faster moving vehicles, particularly on two-lane, two-way highways. Passing ability on two-lane, two-way highways is influenced by a variety of factors including:

1. Traffic volumes of through and opposing traffic
2. Speed differential between the passing and passed vehicles
3. Highway geometry
4. Available sight distance
5. Driver-reaction time and gap acceptance (human factors)

As the functionality of a facility in regard to these characteristics decreases, passing opportunities become fewer, thus increasing the difficulty of vehicles to pass. This difficulty to pass on two-lane, two-way highways can create vehicular travel delay. If vehicles cannot pass slower moving vehicles without delay, platoons begin to form. Vehicle platooning increases the proportion of short headways and decreases mean travel speed on the highway. This reduces the capacity of two-lane, two-way highways consequently decreasing safety and level of service on the roadway. Therefore, delay, indicated by the formation of vehicle platoons, is most often used to access traffic operations on two-lane highway. The following describes current analysis procedures for accessing performance of two-lane, two-way highways based on the concepts discussed previously.

Analysis Procedures for Two-Lane, Two-Way Highways

The main analysis procedures for two-lane highways used in the United States are those outlined in the HCM 2000, the National reference for capacity analysis procedures on highways and other transportation facilities. Also, operations on two-lane, two-way highways may be evaluated using traffic simulation, with TWOPAS being the most known simulation software in North America. The following sections detail theses analysis procedures.

HCM 2000 Analysis Procedures

Highway Capacity Manual: Historical Background In the late 1940's the Bureau of Public Roads and the Highway Research Board's Committee on Highway Capacity joined forces to create a manual that would provide its users with definitions of key terms, a compilation of maximum observed flows, and the initial fundamentals of capacity. From this effort, the first HCM was published in 1950.

The 1950 HCM provided a standard method for highway capacity analysis in the United States. The Manual contained three basic types of capacity: 1) ideal capacity, capacity under ideal conditions, 2) possible capacity, capacity under prevailing conditions, and 3) practical capacity, maximum traffic volume under prevailing conditions without traffic conditions becoming "unreasonable". The latter of these was used to analyze functionality of two-lane, two-way highways, with the performance measure for practical capacity being the operating speed (Luttinen, 2001).

In 1965, a new Highway Capacity Manual was developed and is most-noted for its introduction of the level-of-service concept, which is discussed in more detail later in this chapter. This second edition of the HCM extended the idea of practical capacity from the first HCM to the well-known six levels of service (LOS) scheme. LOS was expressed in terms of operating speed as the governing service measure and the traffic volume limitation as a supplementary service measure (Luttinen 2001). The 1965 HCM outlined a five step process for calculating LOS on two-lane, two-way highways. This procedure involved calculating a base volume and then dividing the given demand volume by the base volume to obtain a v/c (volume to capacity) ratio. This v/c ratio was then used to look up level of service values from a table contained within the Highway Capacity Manual.

After twenty years, a new manual, the 1985 Highway Capacity Manual, was written and in development of this third edition of the HCM, the average speed was considered an inadequate measure of the balance between passing demand and passing supply. Therefore, with this edition of the HCM came a new measure for calculating level of service for two-lane, two-way highways. This measure was known as percent time delay (PTD), which is defined as "the average percent of time that all vehicles are delayed while traveling in platoons due to inability to pass" (TRB, 1985). The HCM 1985 procedures utilized an assumption that cars were traveling in platoons when they were traveling less than their desired speeds at headways less than five seconds. The percentage of vehicles that met these criteria was used as a surrogate measure to PTD.

A few years ago, the fourth edition of the manual, the HCM 2000 renamed the percent time delay (PTD) to percent time-spent-following (PTSF). This was done because the expression was based on time spent traveling in platoons, rather than delay, which was causing confusion with the users of the HCM. Also, it was determined that the five second time headway parameter was too high and users of the manual suggested that a lower value would provide more accurate results. “By changing the definition for when a vehicle is being delayed from a headway of 5 seconds, as given by the Manual, to a headway of 3.5 to 4.0 seconds, more useful level-of-service categories result” (Guell 1988).

Concerns such as this led the Transportation Research Board (formally known as the HRB until the 1970’s) to reconsider the initial value of five second headways and in turn change the value to three seconds in hopes to more realistically quantify the platooning phenomenon on two-lane, two-way highways. From this evolution, the current performance measure for two-lane, two-way highways, PTSF, was developed and introduced to the engineering community. The following sections provide an overview of the HCM 2000 procedures for estimating operational functionality of two-lane, two-way highways. In particular, the section covers the procedure for using PTSF in estimating performance on two-lane, two-way highways.

Highway Capacity Manual: Capacity and LOS Concepts Level of service (LOS) has been used to evaluate the performance of two-lane, two-way highways as early as the 1960’s.

> The concept of level of service was formally introduced in the 1965 HCM and was defined as follows: Level of Service is a qualitative

> measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating cost (Roess 1984, HCM 1965).

According to the HCM (1984), this concept is based completely on measures and characteristics that directly affect the quality of service experienced by facility users. These measures and characteristics are directly perceivable by the individual motorists, and are intended to describe, in relative terms, the quality of the driving experience. From these concepts, the 1965 HCM developed LOS, which has six groups, designated by the letters A-F. Each HCM since 1965 has outlined a procedure for determination of level of service provided by any two-lane highway section with uninterrupted flow. This method for analyzing the performance of two-lane, two-way highways has evolved greatly in the past 40 years, which has led to the current LOS concept as outlined in the HCM 2000 (TRB 2000).

- Level A describes the highest quality of traffic services, when motorists are able to travel at their desired speeds. Generally, this highest quality would result in average vehicle speeds of 90 km/h (55 mi/h) or more. Moreover, drivers are delayed no more than 35 percent of their travel time by slow-moving vehicles
- Level B marks the beginning of stable flow, where speeds of 80 km/h (50 mi/h) are achievable. The demand for passing to maintain desired speeds becomes significant, with drivers being delayed up to 50 percent of the time.

- Level C still experiences stable flow, where the attainable average speed slows to nearly 70 km/h (44 mi/h). Traffic is susceptible to congestion, with delay reaching 65 percent of the travel time.
- Level D experiences unstable flow and represents the highest maintainable traffic volume without a high probability of breakdown in traffic flow. Travel speeds of 60 km/h (37 mi/h) are reasonably maintained, with no motorists experiencing delay for more than 80-85 percent of their travel time.
- Level E represents capacity flow where speeds slow to nearly 40 km/h (25 mi/h). Passing is virtually impossible at LOS E, with platooning becoming intense as slower vehicles or other interruptions are encountered.
- Level F represents forced, congested flow with relatively unpredictable characteristics and traffic demands that exceed capacity.

Two performance measures are used to determine the LOS for two-lane, two-way highways, percent time-spent-following (PTSF) and average travel speed (ATS). As mentioned previously, PTSF is defined as the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of the inability to pass, while ATS is defined as the length of the highway segment divided by the average travel time of all vehicles traversing the segment, including all stopped delay times (TRB 2000). Both PTSF and ATS are used as performance measures for Class I highways, while only PTSF is used for Class II highways. It is important to note that the ATS was selected to be used in coordination with PTSF for Class I highways because it makes

LOS sensitive to design speed and enables the use of the same criteria for both general and specific terrain segments (Luttinen, 2001).

According to the above description of PTSF, it is only concerned with the time when vehicles involuntarily travel in platoons and are unable to obtain their desired speeds due to the inability to pass slower-moving vehicles. According to the HCM 2000, it is often difficult to measure PTSF in the field. A surrogate field measure would be the percentage of vehicles driving at slower than desired speeds being unable to pass slower-moving vehicles. Therefore, the HCM suggests using the percentage of vehicles traveling with headways of less than three seconds as a surrogate measure (TRB 2000). As this surrogate measure has been heavily scrutinized since its employment, it is a major topic of this research.

Besides the surrogate measure described above, the HCM 2000 also outlines a formal procedure for determining PTSF. As described in the HCM 2000, percent time-spent-following can be determined for either two-way segments or directional segments. Two-way segments may include longer sections of two-lane highway with homogeneous cross sections, relatively constant demand volumes, and wide vehicle mixes over the length of the segment. Performance measures for two-way segments apply to both directions of travel combined. Conversely, directional segments carry one direction of travel on a two-lane highway with homogeneous cross sections and relatively constant demand volume and vehicle mix. Directional analysis is most applicable for steep grades and for segments containing passing lanes. A detailed outline of these procedures, including all the input variables required, can be found in Appendix A.

TWOPAS Computer Simulation

Evolution of TWOPAS As was mentioned in the opening, the TWOPAS simulation model is used to evaluate traffic performance on two-lane, two-way highways. TWOPAS is a microscopic computer simulation model for the analysis of traffic behavior on two-lane, two way highways. The predecessor of the TWOPAS model, known as TWOWAF (for TWO WAy Flow), was originally developed in 1978 by the Midwest Research Institute (MRI) and later improved by MRI in 1981. The development of the TWOWAF model is documented in the NCHRP Report 185 titled Grade Effects on Traffic Flow Stability and Capacity (Harwood et al, 1999).

In 1983, the Texas Transportation Institute (TTI) and KLD and Associates made further updates to TWOWAF, which resulted in the version of the model that was used in the development of Chapter 8 of the HCM 1985. This version of TWOWAF had the capability to simulate traffic operations on normal two-lane highways, including both passing and no-passing zones, as well as the effects of horizontal curves, grades, vertical curves and sight distance.

Immediately following the publication of the HCM 1985, MRI developed the TWOPAS model by adding the capability to simulate passing lanes, climbing lanes, and short four-lane sections on two-lane highways. In the 1990's, the University of California Berkeley incorporated a graphical user interface called UCBRURAL into TWOPAS, which greatly simplified the TWOPAS analysis procedure. Recently, improvements were made to TWOPAS and UCBRURAL interface as part of NCHRP Project 3-55(3), (Harwood et al 1999). The improvements made during this project are the latest significant developments to the TWOPAS simulation model.

TWOPAS Simulation Procedures The TWOPAS model simulates traffic operations on two-lane highways by updating the position, speed, and acceleration of each individual vehicle along the highway at one-second intervals as it advances along the road. The model takes into account 1) the characteristics of the vehicle and its driver, 2) the geometrics of the roadway, and 3) the oncoming and same direction vehicles that are in sight at any given time. The following features are found in the TWOPAS simulation model (Harwood et al., 1999):

- Three general vehicle classifications – passenger cars, recreational vehicles, and trucks.
- Roadway geometrics specified by the user which include: horizontal curves, grades, vertical curves, sight distance, passing lanes, climbing lanes, and short four-lane sections.
- Traffic controls specified by the user, of particular importance, passing and no-passing zones.
- Traffic streams at each end of the simulated roadway generated in response to user-specified flow rate, traffic mix, and percent of platooned traffic.
- Variations in driver behavior based on empirical data.
- Driver speed in unimpeded traffic based on user-specified distribution of driver desired speeds.

- Driver speed in impeded traffic based on a car-following model that simulates driver preferences for following distances (headways). This is based on three concepts: 1) relative speeds of leader/follower, 2) desired speeds of drivers, and 3) driver's desire to pass the leader.
- Driver decisions concerning initiating passing maneuvers, continuing/aborting passing maneuvers, and returning to normal lane, based on empirical data.
- Driver decision concerning behavior in passing/climbing/four-lane sections, including lane choice at beginning of added lane, lane changing/passing within added lanes and at lane drops, based on empirical data.
- Processing and updating of vehicle speeds, accelerations, and positions at intervals of 1 second of simulated time.

Analysis of Two-Lane, Two-Way Highways: Limitations of Current Procedures

Since the introduction of the HCM 2000, a few studies have been conducted to evaluate the new procedures in estimating traffic performance on two-lane, two-way highways. These studies include both theoretical and empirical validation of the HCM 2000 procedures for estimating performance on two-lane, two-way highways. The purpose and results from these studies are given below.

In the year 2000, Luttinen analyzed PTSF as a performance measure for two-lane, two-way highways using data collected in Finland (Luttinen 2001). In his study, the estimation of PTSF and its adjustment for prevailing conditions in the HCM 2000 was compared with both an exponential headway model as well as traffic flow data from 20 different two-lane, two-way highways in Finland. Results of the study suggested that the HCM 2000 procedures significantly overestimate the PTSF. Furthermore, the study showed that the PTSF estimates obtained from the directional analysis are higher than those obtained from the two-way analysis.

In the year 2002, Luttinen (2002) completed a second study that evaluated the sources of uncertainty in the HCM 2000 procedures for two-lane, two-way highways. Results of this study showed that there are questions in accuracy and precision of the adjustment factors (see Appendix A for adjustment factor) used with the HCM 2000 method. Discrepancies were found between the results from two-way and directional analyses under various traffic flow rates.

Also in the year 2002, Dixon et al. (2002) evaluated the HCM 2000 two-lane highway directional, two-way, and passing lane analysis procedures using field data collected from a 9.8 km section of US -95 in Idaho. Consistent with Luttinen's studies, this study showed that the two-way analysis procedure was more accurate than the directional method, although both procedures substantially overestimated the PTSF. The following discussion summarizes these studies in further detail.

According to Luttinen (2001), a good performance measure of traffic flow should portray the following five main qualifications:

1. reflect the users' perception of the quality of traffic flow,
2. be easy to measure,
3. be compatible with the performance measures of other types of highway facilities,

4. describe both undersaturated and saturated conditions, and
5. as far as possible, be useful also in safety, economic and environmental analyses.

It should be noted that it is probable that no performance measure is good in regard to all of these characteristics. Nonetheless, it is important to ascertain the capability of PTSF as a performance measure in respect to these qualities. In accordance with the scope of this project, only the first two qualifications have been assessed. In regard to the first item, Hardwood (1999) stated that PTSF represents two important aspects of the LOS concept on two-lane, two-way highways, 1) the freedom to drivers to maneuver and 2) the comfort and convenience of travel. From this description, it would seem that there is some connection between PTSF and user sensitivity. However, as Luttinen (2001) states, there has been no formal connection between PTSF and user's perception reported.

More importantly, in regard to the second item, the HCM 2000 reports that up to this point, PTSF has been difficult to measure in the field. This is the reason for the past to HCM publications to suggest the use of time headways smaller than a certain cut-off value as a surrogate measure to PTSF. Chapter 3 will discuss in detail, the development and accuracy of the HCM surrogate measure for estimating PTSF.

Furthermore, Luttinen (2001) questioned the validity of this surrogate measure, and therefore completed a study using a negative exponential headway distribution as shown in Figure 2 to model the proportion of short headways in a random flow without any vehicular interaction. The analysis was completed for a range of traffic volumes, 0 to 3000 vehicles per hour, and a range of directional distribution factors, 0.5 up to 1.0, represented by the various parabolic lines in the figure. The purpose of the graph is to represent the number of vehicles traveling at less than three second headways under random traffic flow, which is the worst case scenario.

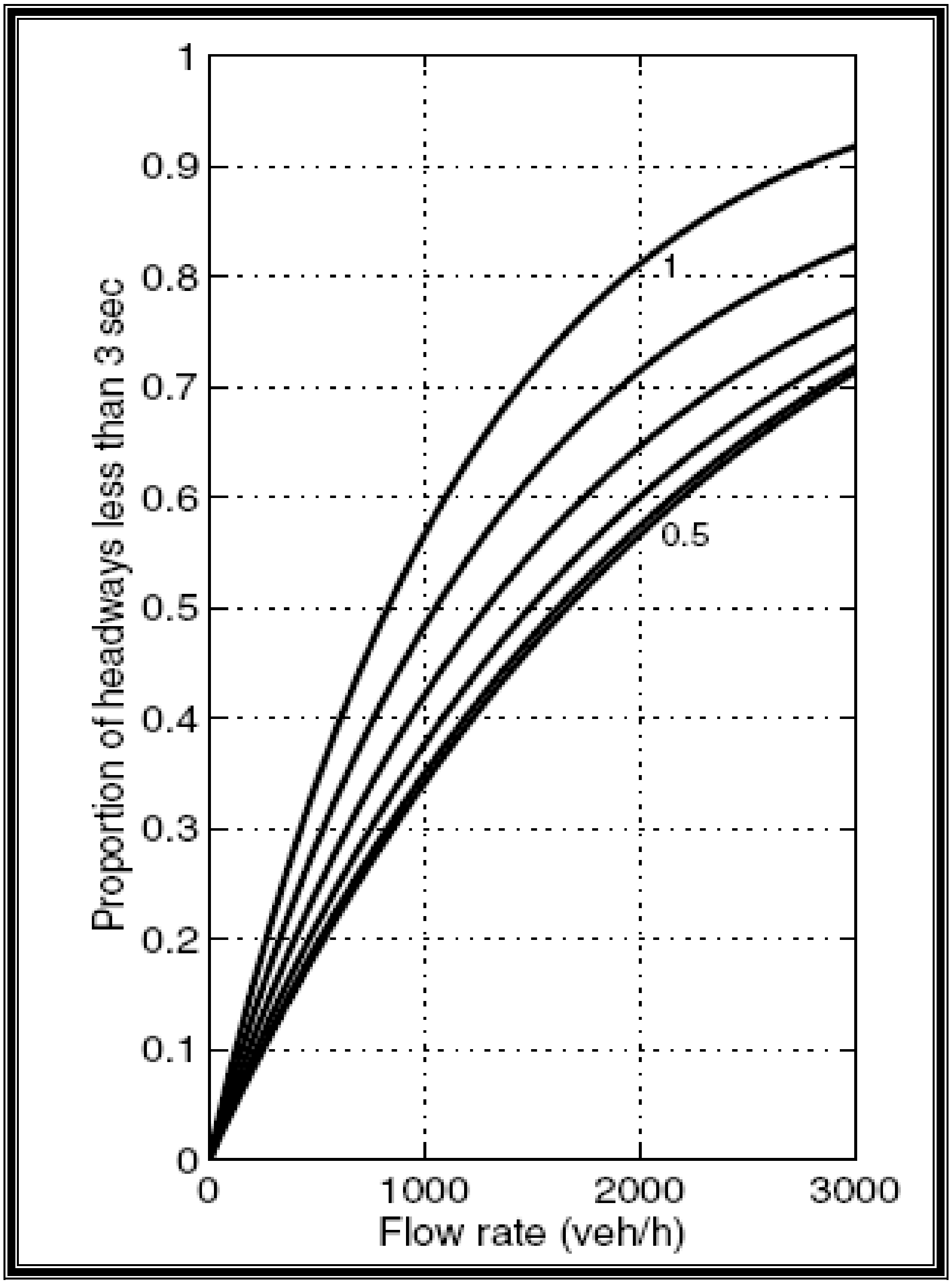

Figure 2 Negative Exponential Headway Distribution (Luttinen (2001))

The analysis shows that the proportion of headways less than 3 seconds (the HCM 2000 headway cut-off value) composes a significant amount of traffic flow, nearly half the vehicles at a flow rate of 1000 vehicles per hour. Specifically, this means that even when there is no interaction between vehicles, nearly half of the vehicles would still be traveling at or less than three second headways. This shows that the use of three second headways as a surrogate measure for estimating the PTSF is most likely an overestimate.

Another study completed by Dixon, et al. (2002) responded to the need for validating the HCM 2000 procedures using conditions observed in the United States, which until that point had not been done. This assessment was completed for the two-way, directional, and passing lane analysis using field data collected in Idaho. The study found that the HCM two-way, directional, and TWOPAS estimates of the PTSF are too high in comparison with actual field data, as can be seen in Table 1. This is in direct agreement with the conclusion drawn by Luttinen (2001, 2002).

Table 1 Comparison of HCM two-way, directional, and TWOPAS PTSF (Dixon et al, 2000)

Time Interval (1)	Field PF[a] (2)	HCM Directional Analysis,[b]PTSF (3)	HCM Two-way Analysis, PTSF (4)	TWOPAS	
				PF (5)	PTSF (6)
10:15-10:30	13.6	45.0	36.9	36.3	33.6
13:30-13:45	23.1	51.4	43.1	43.7	40.7
13:45-14:00	20.1	52.5	44.2	45.6	42.6
15:45-16:00	24.1	56.2	48.0	49.9	46.5

[a] Weighted average of northbound and southbound observed PF values.
[b] Weighted average of northbound and southbound estimated PTSF values.

It is clearly shown in this table that the current HCM procedures overestimate the PTSF values by 200% or more. Dixon et al. (2002) suggest that some of the overestimation stems from two possible sources:

1. Inconsistency between the level-terrain highway alignment used in TWOPAS to generate the HCM 2000 analysis procedure and the two highway alignments used in the study,
2. Inaccurate mathematical modeling of traffic conditions represented in the field studies discussed in Dixon's paper, "Field Evaluation of Highway Capacity Manual 2000 Analysis Procedures from Two-Lane Highways."

Another observation made by the same study was that calculating PTSF using the HCM two-way and directional analyses provides different results. "It can be seen that on average the two-way analysis is substantially less than the directional analysis and that the two-way analysis more closely approximates the field data…" (Dixon et al., 2002). Luttinen (2001) made a similar observation concerning the two types of the HCM analysis being incompatible. "One source of uncertainty in the PTSF analysis is the discrepancy between the results of directional analysis and those of two-way analysis" (Luttinen 2002). Figure 3 shows that the two-way segment analysis provides lower values of PTSF than the directional segment analysis (Luttinen, 2002).

In response to the issues addressed by Luttinen (2001, 20002) and Dixon et al. (2002), the NCHRP and the Midwest Research Institute (MRI) undertook research in 2003 to address these issues with the HCM 2000 two-lane, two-way highway analysis procedures. The NCHRP Project 20-7 (160) and MRI Project 110252 attempted to address the overestimation of PTSF in the HCM 2000 directional segment procedures. The project reported that the problem was alleviated by revising the PTSF vs. flow rate curves and the adjustment factor for directional split and no-passing zones (NCHRP-MRI, 2003).

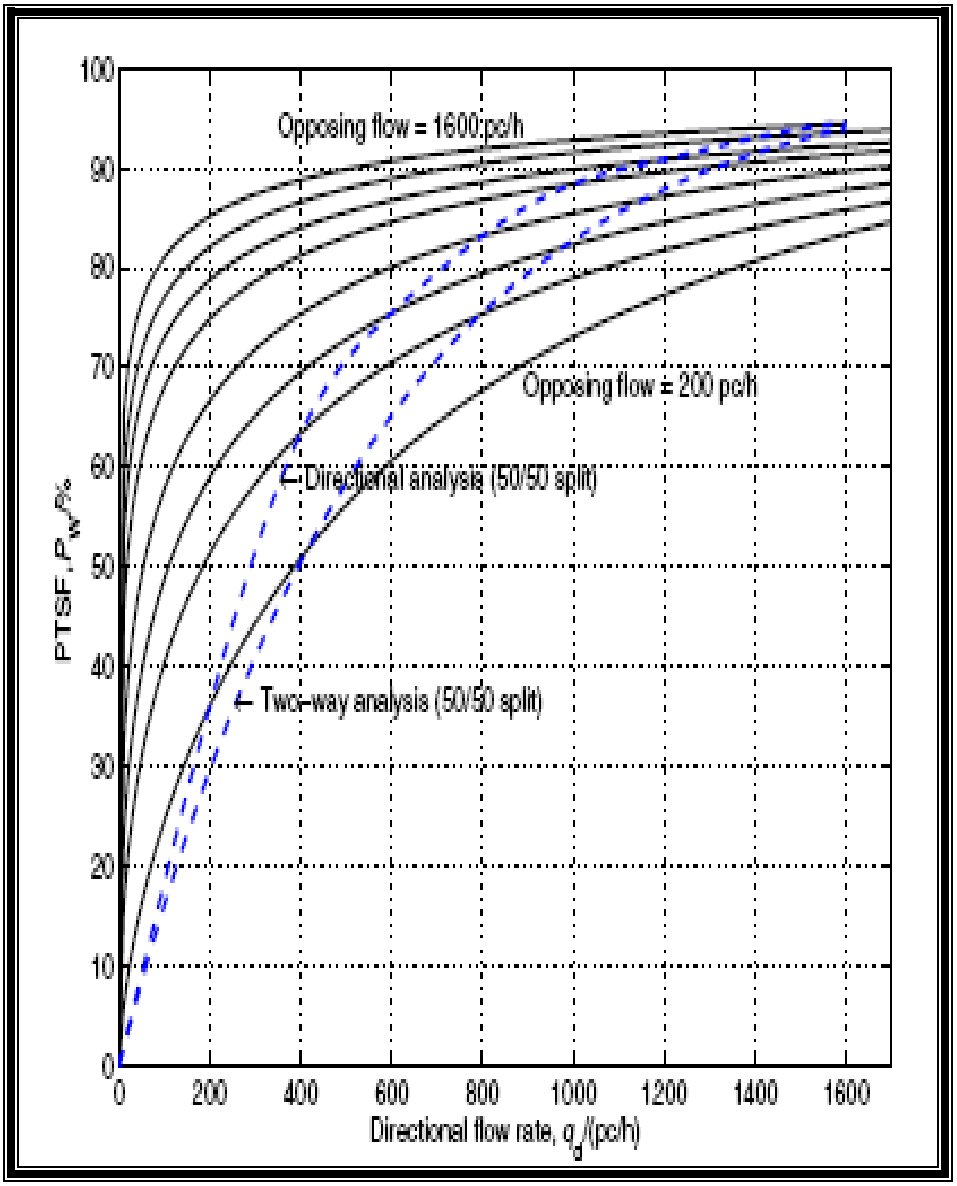

Figure 3 PTSF in Directional Segments (Harwood et al, 1999)

Chapter Summary

This chapter discussed the current literature in regard to operation and performance of two-lane, two-way highways. In particular, the chapter discussed the past and current procedures for estimating the performance of two-lane, two-way highways. The most important of these procedures discussed was the HCM 2000 procedures, which using LOS given by the performance measure PTSF to estimated performance on two-lane, two-way highways. Finally, the chapter investigated current studies aimed at validating the HCM 2000 two-lane, two-way analysis procedures.

CHAPTER 3

REVIEW OF CURRENT HCM PROCEDURES

As stated in the previous chapter, the current HCM procedures for estimating the functionality of two-lane, two-way highways are concerned with establishing the performance measures PTSF and ATS. The following chapter discusses the formulation of these HCM 2000 procedures and reviews their effectiveness.

Formulation of Current Procedure

The HCM 2000 procedure for calculating PTSF was formulated from a study conducted for the National Cooperative Highway Research Program (NCHRP), Project 3-55(3) (Harwood et al., 1999). In this study, a survey was conducted to determine the most appropriate service measure for two-lane, two-way highways. One part of the survey asked users of Chapter 8 of the HCM 1985, the two-lane highway analysis chapter, about the features that should be added to the HCM procedure for analyzing two-lane, two-way highways. The results from the study helped formulate the HCM 2000 procedures, and a brief summary of this survey is provided below:

> "Based on a review of the advantages and disadvantages of candidate service measures, the research team concluded that the most appropriate service measure for two-lane highways is the combination of percent time delay and average travel speed. In response to HCM user confusion over the meaning of the term percent time delay, the research team concluded that the meaning of this term would be clearer if it were renamed *percent time-spent- following* (PTSF) (Harwood et al., 1999)."

After the analysis team determined that a combination of PTSF and ATS is the most appropriate service measure for two-lane, two-way highways, they completed analyses of these performance measures using the computer simulation model TWOPAS. From these analyses, they derived equations for determining PTSF as outlined in the HCM 2000, which can be found in Appendix A. To complete the computer simulation, a list was made that described various traffic situations that can be experienced by vehicles during any point in time. These six vehicle states as used in TWOPAS were:

1. Free vehicle, unimpeded by others
2. Overtaking a leader, but still 2.4 m/s (8 ft/s) faster than the leader
3. Following a leader
4. Close following with interest in and capability of passing
5. Passing another vehicle
6. Aborting a pass

PTSF was determined from the TWOPAS simulation as the percentage of total travel time that vehicles spend in TWOPAS States 2 through 6 (i.e., not in State 1) (Hardwood et al., 1999). Furthermore, the TWOPAS model was used to compare three different forms of performance measures based on platooning traffic. As stated by Harwood et al. (1999), these measures were:

1. PTSF based on percentage of time spent in TWOPAS States 2 through 6
2. PTSF based on PTSF at various headways from 2 to 6 s
3. Average spot platooning based on various headways from 2 to 4 s

Table 2 displays the results from this analysis. As shown in the table, the results from the comparison "indicated that PTSF based on TWOPAS States 2 through 6 agrees very closely with both PTSF in platoons based on a 3-s headway and average spot platooning for a 3-s headway" (Hardwood et al., 1999). From this comparison, the surrogate measure for estimating PTSF of three second headway was formulated. "… it was determined that the revised HCM chapter should recommend a 3-s headway, rather than a 5-s headway, for estimating PTSF in the field" (Harwood et al., 1999)

Table 2 Comparison of Percent Time Spent Following, as Determined with the TWOPAS Model, to Various Headway Criteria (taken from NHCRP Project 3-55(3))

Flow rate (veh/h)	Percent time spent following						Average spot platooning		
	TWOPAS State 2-6	Based on headway of:					Based on headway of:		
		2 s	3 s	4 s	5 s	6 s	2 s	3 s	4 s
800	51.3	34.4	53.5	61.9	64.9	66.7	33.6	52.4	60.6
	50.0	32.5	50.8	59.6	61.9	64.0	31.5	50.1	58.3
	50.5	32.9	51.4	60.4	62.7	64.7	32.2	50.2	58.9
1,200	64.5	43.7	64.8	73.5	75.7	77.1	42.7	63.9	72.4
	65.8	42.8	65.8	74.1	76.1	77.6	41.4	64.0	72.5
	66.8	44.2	66.8	76.0	78.0	79.5	43.5	66.0	74.7
1,600	74.1	49.4	73.0	82.4	84.0	85.2	48.7	72.4	81.6
	73.6	48.6	72.6	82.1	84.0	85.2	47.6	71.7	81.0
	74.9	49.0	73.8	83.9	85.4	86.4	48.2	72.9	83.0
	Avg Diff	−21.6	0.1	9.1	11.2	12.8	−22.5	−0.9	7.9

Note: A 50/50 directional split of traffic and 5 percent trucks were assumed for all simulation runs

As this surrogate measure has been in use by the transportation engineering community for around five years, it has had sufficient time to be studied and analyzed. Those analyses suggest that the HCM 2000 surrogate measure of three-second headway greatly overestimates the actual PTSF using field measurements. The next section will explain this in more detail and suggest possible flaws in the formulation of the surrogate measure that may be related to this overestimation.

Flaws in Formulation of Current Procedure

There appears to be two fatal flaws in the formulation of the three second surrogate field measure used in the HCM 2000. First, the assignment of vehicle states 2-6 as all being trapped in platoons unable to pass is questionable. Particularly, considering vehicle travel states such as passing another vehicle or overtaking a leader as being part of the performance measure PTSF seems suspect. The HCM 2000 defines PTSF "as the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of the inability to pass" (TRB, 2000). As these vehicles are completing a passing maneuver, it would seem that vehicles traveling in states 2 and 5 are no longer traveling in platoons behind slower vehicles with the "inability to pass". It appears that assigning the travel time vehicles spend in these states as a component of PTSF is a possible reason for the overestimation linked with the HCM 2000 procedures.

The second flaw is concerned with the use of computer simulation to formulate the performance measure without employing any empirical analysis to test the validity of the simulation. As computer simulation is based on algorithms developed to depict real-life situations, it is imperative that these algorithms be calibrated and validated using empirical data prior to using simulation results in developing practical procedures. The values shown in Table 2 are merely outputs of a computer simulation model that may not accurately portray what happens in real life situations. It seems suspect that the procedure was based solely on the outputs of a computer simulation model, instead of on empirical data from two-lane, two-way highways or some combination of both.

The two fatal flaws discussed above appear to be possible reasons for overestimation and/or erroneous results provided by the HCM 2000 method for determining PTSF. To shed more light on the effectiveness of the HCM 2000 procedures for two-lane, two-way highways in estimating the PTSF, a few analyses were conducted using both theoretical and empirical approaches and are discussed in the following section.

Consistency between PTSF in Theory and Practice

The HCM 2000 procedures for measuring and estimating the PTSF involves two implicit assumptions that have serious implications on the validity of the approach. These assumptions are:

1. Any vehicle traveling in a platoon (i.e. in car-following mode) is there because of its inability to pass the lead vehicle(s). This implies that any vehicle that is part of a platoon always has a desired speed that is greater than the speed of the lead vehicle (i.e. the speed of the platoon).
2. If the time headway between the lead and the following vehicle(s) is less than a pre-specified cut-off value, then the following vehicle(s) will be in a car-following mode (5 seconds in HCM 1985 and 3 seconds in HCM 2000).

The assumptions above are a source of inconsistency between the PTSF concept and the procedures for measuring and estimating the PTSF on two-lane, two-way highways. From the first assumption, being part of a platoon is not an adequate indication that the desired speed of the following vehicle is greater than that of the lead vehicle. Drivers may prefer to maintain comfortable distance headways from the lead vehicles without the desire to increase speed.

Furthermore, the second assumption implies that any vehicle with time headway less than the cut-off value is in car-following mode, i.e. maintaining the minimum gap distance from the lead vehicle. Those cut-off values are arbitrary in nature and not based on well-established studies or empirical observations. In the following discussions, a few evidences are outlined that clearly refute the above assumptions.

- Evidence I – The first evidence is a comparison between the minimum safe distance headway as suggested by two well-known car-following theories and the distance headways that correspond to the 3-second and 5-second time headways used to estimate the PTSF in the HCM 2000 and 1985, respectively.
- Evidence II – This evidence is theoretical. Because short time headways are used as a surrogate measure to the PTSF, it is instructive to investigate the proportion of short headways in a random flow without any vehicular interaction, i.e. the distribution of time headways according to the shifted negative exponential distribution.
- Evidence III – Vehicles on the rightmost lane of a multi-lane highway may be part of platoons even in the lack of any restriction on passing maneuvers. Under moderate and low traffic levels, passing opportunities for a vehicle in the rightmost lane are typically available and therefore not a cause for being part of a platoon.

Evidence I was tested using Forbes' and Pipes' car following models to determine minimum safe time headways and then compared to the values from the HCM 1985 and 2000. Evidence II was tested by first fitting a shifted negative exponential distribution to various hourly flow rates. From this, the percentage of vehicles having time headways less than the HCM 2000 surrogate measure was ascertained. Evidence III was tested by collecting data from the rightmost lane on Interstate 90 near Bozeman, MT and determining the percentage of vehicles traveling at or less than 3 second headways. The reason for using Interstate data is discussed in the following sections. The first two evidences are based on theoretical testing, while the final evidence is based on empirical testing, which are discussed in detail in the following sections.

Theoretical Testing

Car Following Theories

Two well-known car following theories were chosen to analyze the accuracy of using 5 and 3 seconds time headways as a surrogate measure for percent time spent following. The two car following theories were developed by Pipes and Forbes (May 1990). According to Pipes' Car Following Theory, the safe distance headway between any two successive vehicles (in car-following mode) can be calculated using the following equation:

$$d_{MIN} = 1.36\left[\dot{x}_{n+1}(t)\right] + 20 \qquad \text{Equation 1}$$

where d_{MIN} = minimum distance headway (ft)
$\dot{x}_{n+1}(t)$ = speed of following vehicle (miles per hour)

The previous theory characterizes vehicle motion in the traffic stream according to a rule from the California Motor Vehicle Code. Namely, "a good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between your vehicle and the vehicle ahead for every ten miles per hour of speed at which you are traveling" (May 1990). From this rule and an assumption that the average vehicle is 20 feet in length, the above equation was formulated.

The second theory, Forbes' Car Following Theory, provides an equation for calculating distance headways as follows:

$$d_{MIN} = 1.50\left[\dot{x}_n(t)\right] + 20 \qquad \text{Equation 2}$$

where d_{MIN} = minimum distance headway (ft)

$\dot{x}_n(t)$ = speed of lead vehicle (miles per hour)

In his theory, Forbes used the assumption that car-following behavior was controlled by the reaction time needed for the following vehicle to perform two actions, namely: 1) perceive the need to decelerate and 2) apply the brakes. This means that the time gap between the rear of the lead vehicle and the front of the following vehicle should always be equal to or greater than this reaction time, assuming that the vehicles have equivalent braking capabilities. Therefore, it can be said that the minimum time headway is equal to the reaction time plus the time required for the lead vehicle to traverse a distance equivalent to its length. Combining this idea with the assumptions that reaction time is 1.5 seconds and average vehicle length is 20 feet, the above equation was formulated (May 1990).

To find the corresponding headway values using the HCM 1985 and 2000 methods, the time headways of 5 and 3 seconds were simply converted into distance headways by multiplying the headway value by vehicle speeds. Results of this analysis are shown in Table 3.

From the table, it can be seen that the minimum time headways under the Pipes' and Forbes' Car Following Theories are nearly half the values obtained from the HCM 2000 method and roughly one third of the HCM 1985 values. This means that for normal driving conditions, many of the cars classified as traveling in vehicular platoons under the HCM 1985 and 2000 procedures would be considered as traveling in free flow mode at safe headways under the Pipes' and Forbes' Theories. As the HCM procedures provide values that are 2 to 3 times larger than the car following theories, it becomes evident that the HCM procedures have some inaccuracies when used for estimating the PTSF on two-lane, two-way highways.

Table 3 Distance Headways (ft) For HCM Procedures versus Car Following Theories

Theory	Speed(mph)								
	35	40	45	50	55	60	65	70	75
Pipes Car Following	89.8	99.8	109.8	119.7	129.7	139.7	149.7	159.6	169.6
Forbes Car Following	97.0	108.0	119.0	130.0	141.0	152.0	163.0	174.0	185.0
HCM 1985 - 5 second	256.7	293.3	330.0	366.7	403.3	440.0	476.7	513.3	550.0
HCM 2000 - 3 second	154.0	176.0	198.0	220.0	242.0	264.0	286.0	308.0	330.0

*Assumed a vehicle length of 20 feet
*Assumed a reaction time of 1.5 seconds for Forbes' Theory

<u>Shifted Negative Exponential Distribution</u>

Another technique used to verify the HCM 1985 and 2000 procedures was to fit various traffic volumes to a shifted negative exponential distribution and determine the percentage of headways that would fall beneath the 5 and 3 seconds values. The negative exponential distribution is used frequently in transportation engineering to represent random occurrences, like the time headways of a two-lane, two-way highway. "The negative exponential distribution is the mathematical distribution that represents the distribution of random intervals such as time headways" (May, 1990).

A procedure was taken from May (1990) to complete the negative exponential distribution analysis. Specifically, the procedure outlines using a modified negative exponential distribution, known as a shifted negative exponential distribution. The equation used to find the aforementioned percentage of headways is based on a probability density function and is as follows:

$$e^{-(t-\alpha)/(\bar{t}-\alpha)} \quad \text{Equation 3}$$

where t = time headway being investigated (seconds)

$\bar{t}$ = mean time headway given by $\bar{t} = \frac{3600}{V}$

V = hourly flow rate (vph)

α = minimum expected time headway

The above equation gives the probability that headways will be equal to or larger than the headway being investigated, or $P(h \geq t)$, where h is the individual time headway. As probability is a value in the range [0, 1], the value for the percentage of headways less than the headway being investigated could be found by simply subtracting the $P(h \geq t)$ value from 1, or $P(h \leq t) = 1 - P(h \geq t)$. One step in developing a shifted negative exponential distribution is to assume values for the minimum expected time headway, known as α. May suggests a range of values from 0.5 to 2.0 seconds, and therefore the test was completed using a series of values within this range. Table 4 displays the results, in percentage form, for calculating the HCM 1985 and 2000 surrogate measures using the shifted negative exponential distribution. It can be seen from this table that the percentage of vehicles traveling at or less than 5- or 3-second headways are significant for all flow rates.

Luttinen (2001) performed a similar analysis using a negative exponential headway distribution, as was shown in the previous chapter. As with the analysis conducted for this study, the analysis completed by Luttinen (2001) shows that the proportion of headways less than 3 seconds composes a significant amount of the traffic volumes, again nearly half the vehicles at a flow rate of 1000 vehicles per hour. This means that under the HCM 2000, over half the cars traveling at the time this flow rate occurred would be in car following mode and thus experiencing delay. This analysis is for random arrivals within the traffic stream in which no vehicles interact with each other. As vehicle interactions are frequent on two-lane, two-way highways, especially as volume increases, the percentages shown in Table 4 would be considerably higher under normal conditions. Therefore, it seems suspect to use a headway threshold value to model the number of vehicles traveling involuntarily in platoons.

Table 4 Percentage of Time Headways Equal to or Less than HCM Surrogate Measure

		Hourly Flow Rate, vph						
	α	200	400	600	800	1000	1200	1400
HCM 1985 5 seconds	0.5	22.7	41.1	55.9	67.5	76.6	83.5	88.6
	1	21.0	39.3	55.1	68.1	78.5	86.5	92.2
	1.5	19.1	37.3	54.1	68.9	81.1	90.3	96.2
	2	17.1	34.9	52.8	69.9	84.7	95.0	99.5
HCM 2000 3 seconds	0.5	13.3	25.5	36.5	46.5	55.4	63.2	70.1
	1	11.1	22.1	33.0	43.5	53.7	63.2	72.0
	1.5	8.7	18.1	28.3	39.3	51.0	63.2	75.3
	2	6.1	13.3	22.1	33.0	46.5	63.2	82.6

Empirical Testing

Though the theoretical approaches described in the previous section are important in determining the validity, or lack thereof, of the HCM 1985 and 2000 procedures, completing empirical analyses can build a more compelling case. The purpose of using empirical data for this research is to show, using real life data, that time headways less than 3 or 5 seconds do not necessarily represent being trapped in a platoon with the inability to pass. This point can be seen more clearly from an example.

At a speed of 60 mph, the distance headways of vehicles traveling at either 5 or 3 second time headways are 440 and 264 feet, respectively. These values represent per lane densities of 12 and 20 vehicles per mile per lane, corresponding to LOS on freeways of A and B, respectively. Although freeways are very different facilities than two-lane, two-way highways, this shows that travel at headways near 5 and 3 seconds can occur frequently, even when the option to pass is always available. This example was developed into an experiment using actual field data from Interstate 90 near Bozeman, MT.

Field Data – Interstate 90, Bozeman, MT

As stated above, the reason for using interstate data is that it represents a facility in which passing opportunities are generally always available under moderate traffic levels. This is important to the study because it can show that even when passing opportunities are not hindered, cars may still travel at time headways less than 3 and 5 seconds.

Data was collected near mile marker 306 on Interstate 90 near Bozeman, MT using Jamar Technologies' Trax 1 traffic counters. A detailed description of the counters and the method used to collect and process data is described in further detail in Chapter 5. One complication of using these particular traffic counts is that the accompanying computer software provided by Jamar Technologies, TraxPro, only processes vehicle distance gaps (the distance between the rear of the lead vehicle and the front of the following vehicle). As this study is interested in distance headways (the distance between the front of the lead vehicle and the front of the following vehicle) rather than distance gaps, the raw time stamped data was manually processed using Microsoft Excel. From this manual processing, vehicle headways were determined for all vehicles in the Interstate 90 data set (roughly 13500 vehicle observations).

Using the traffic volume counts for the Interstate 90 data set, one peak hour (the hour with the highest traffic volume) and one off-peak hour (an hour with relatively low traffic volume) were selected for analysis. The vehicle count during the peak hour was 819 vehicles corresponding to a volume-to-capacity ratio (v/c) of around 0.4, which is considered moderate traffic flow. The traffic count during the off-peak hour was 371 vehicles, corresponding to a v/c of around 0.19, which is considered very low traffic level. After each traffic volume was established, vehicle time headways were determined for the two predetermined hours and divided into three categories:

1. Headways less than 3 seconds
2. Headways between 3 seconds and 8 seconds
3. Headways larger than 8 seconds

The first range was chosen based on the HCM 2000 classification of PTSF, namely 3 second headways. The cut off between ranges two and three of 8 seconds was an arbitrary value chosen to represent vehicles that were traveling outside of any platoons. To clarify this value, a car traveling at 70 mph and time headway of 8 seconds would be roughly 830 feet from the next closest vehicle in the traffic stream. Therefore, it would be reasonable to assume that this car is traveling outside of any influence from other vehicles. As 5-second headways are no longer used as a surrogate measure under HCM procedures, empirical analysis was only completed for the 3-second surrogate measure. Figure 4 shows a graphical representation of the Interstate 90 headway counts based on the three categories.

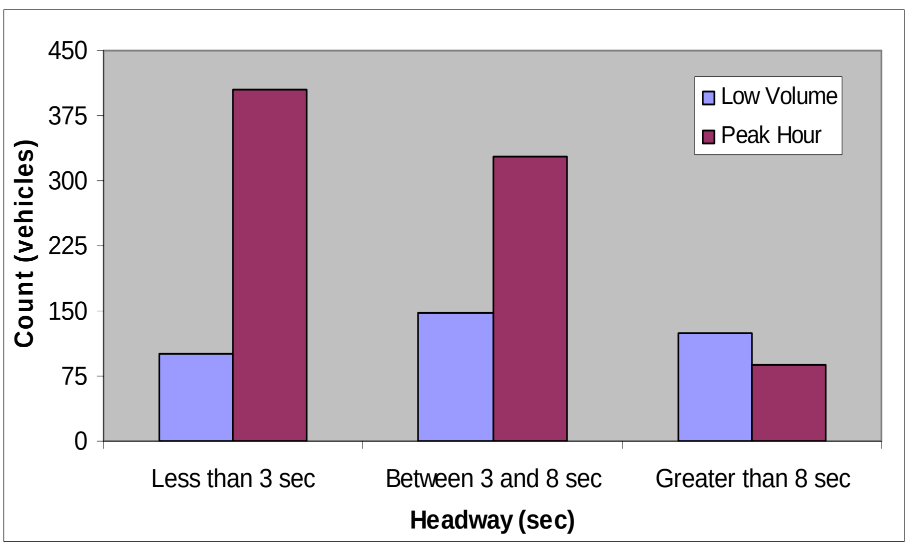

Figure 4 Headway Count Distribution for I-90

A few interesting assessments can be made from Figure 4. First, it can be seen that the data set follows a predestined pattern concerning moderate and low traffic volumes.

“When traffic volumes on a given roadway are low, headways tend to be high and motorists are seldom delayed. As volumes approach capacity, the proportion of vehicles found in platoons increases, and delay increases” (Gattis et al, 1997). Under peak hour traffic, it can be seen that the frequency (number of occurrences) of small time headways is higher than the frequency of large time headways. This corresponds to the idea that as more vehicles are added to the traffic stream, time headways are going to decrease.

Further analysis was completed on the I-90 data set to determine the percentage of headways occurring under the three different categories. The analysis of this data set showed that under peak hour traffic, the number of headways less than 3 seconds was determined to comprise a significant amount of the total number of headways. Figure 5 shows the percentages of headways under the three categories for the peak and off-peak hours investigated in this analysis.

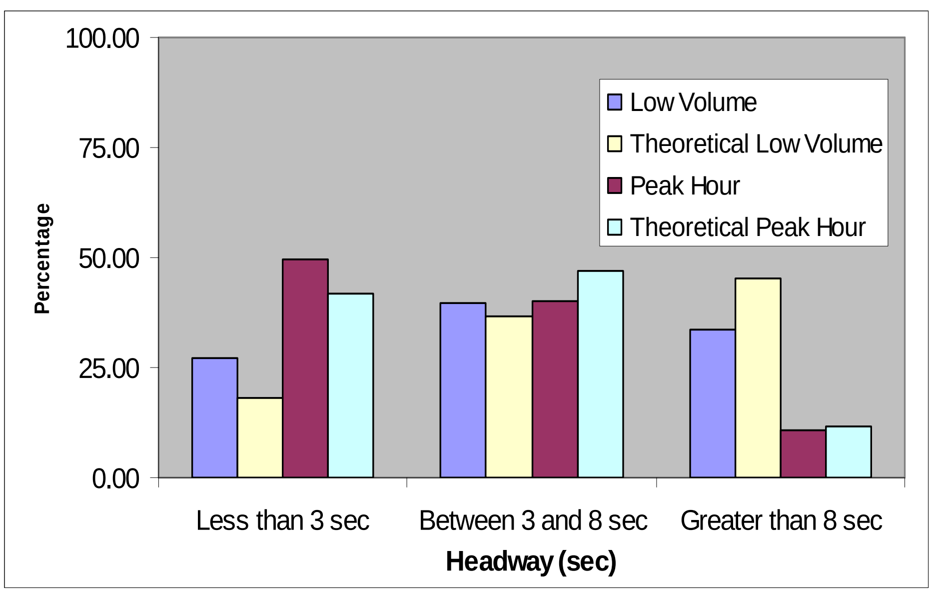

Figure 5 Percentage of Vehicle Headways for I-90 Data

From this figure, it can be seen that roughly 50 percent of the time headways occurring during the peak hour were less than 3 sec. Under the low traffic volume, the number of headways less than 3 sec comprised a significantly smaller amount, around 27 percent of the time headways. However, this value of 27 percent of vehicles traveling at headway less than 3 sec is a considerable amount considering the low traffic volumes and the constant passing opportunity that interstate facilities provide. These high percentages show that many vehicles travel at headways less than 3 sec, even when the opportunity to pass is always present.

One of the concerns regarding this analysis was the location in which the data was collected. Specifically, the presence of on- and off- ramps near the study site may have an effect on the true proportion of vehicles traveling at less than a 3-second headway. One way to determine the affect of these ramps is to compare the data set to a theoretical model that simulates random operations, specifically, a negative exponential distribution. This has been completed and the results can also be seen in Figure 5.

If the ramps have no effect on the data, the results should be relatively close to those provided by the negative exponential distribution. Therefore, the traffic volumes obtained from the peak and off-peak hours were plugged into the shifted negative exponential distribution. It can be seen from Figure 5 that the theoretical values for time headways less than 3 seconds provided by the shifted negative exponential distribution are considerably accurate when compared to actual data. This shows that the data collected on Interstate 90 closely represents random operation. The nearby on- and off-ramps may account for a small percentage of vehicle headways less than 3 seconds, but the shear number of headway less than 3 seconds goes beyond the effect of just the on- and off- ramps. Therefore, the results from the analysis still show that a large amount of vehicles travel at headways less than 3 second, even when passing opportunities are always present.

Chapter Summary

From the theoretical and empirical analyses that were completed concerning the HCM 1985 and 2000 surrogate measures for estimating the PTSF, it has been shown that many vehicles travel at headways less than 3 or 5 seconds, regardless of whether they are traveling in car-following mode or at free flow state (without interaction with other vehicles in the traffic stream). This in turn means that using this suggested surrogate measure for determining the PTSF will yield inaccurate values in the form of gross overestimates of the PTSF. Furthermore, from the analyses presented in this chapter, it is fair to state that: (1) not all vehicles in a platoon travel at speeds that are less than their individual desired speeds, and (2) not all vehicles with short time headways (less than the HCM cut-off value) are in car-following mode due to being in a platoon. Based on these two statements, it becomes clear that vehicles that are part of a vehicular platoon should belong to one of the following two distinct groups of vehicles:

1. Vehicles that travel voluntarily in a platoon at nearly their desired speed (same as platoon speed) while maintaining comfortable distance headway from the lead vehicle.
2. Vehicles that travel involuntarily in a platoon at less than their desired speeds unable to pass slow-moving vehicles.

CHAPTER 4

MEASURING PTSF – PROPOSED NEW APPROACHES

As was shown in Chapter 3, the method for estimating percent time-spent-following in the current edition of the Highway Capacity Manual is inaccurate when used to assess level of service on two-lane highways. For this reason, it is the objective of this research to assess and evaluate two proposed new techniques to estimate and measure the major performance indicator on two-lane highways, i.e. the PTSF (Al-Kaisy 2005). This chapter sheds light on the concept and the computational procedures of the new techniques that are essential in understanding the analyses included in the current research.

Before introducing the new techniques, it is imperative to discuss the concepts behind the unique characteristics of traffic operations on two-lane, two-way highways. According to the HCM 2000, motorists using two-lane, two-way highways are forced to adjust their individual travel speed as volume increases and the ability to pass declines (TRB 2000). If the need to pass is not met by the facility, the effect is that fast-moving vehicles will be involuntarily traveling in car-following mode at lower than their desired speed. This concept, known as vehicular platooning, is the basis for the development of the new approaches for measuring performance on two-lane, two-way highways.

A platoon is described by the HCM 2000 (TRB 2000) as "a group of vehicles or pedestrians traveling together as a group, either voluntarily or involuntarily because of signal control, geometrics, or other factors." An example of a vehicle platoon is shown graphically in Figure 6. In Figure 6, the shaded vehicles represent those vehicles involuntarily traveling in the platoon at lower than their individual desired speeds. The white vehicles represent those vehicles voluntarily traveling in the platoon at their desired speed or at a comfortable speed that is close to their desired travel speed.

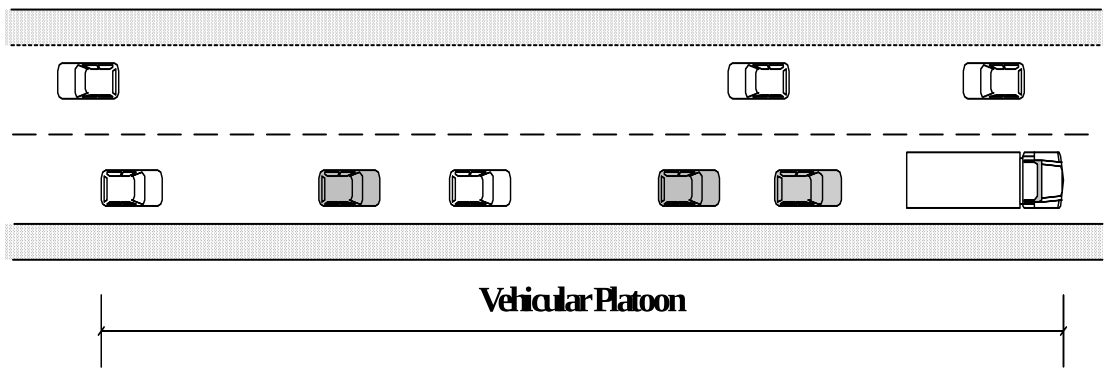

Figure 6 A Vehicular Platoon Behind a Truck on a Two-Lane Highway

While average speed may vary on two-lane, two-way highways for various reasons such as speed limit, functional classification, etc., the restriction on passing maneuvers and its effect on drivers' satisfactions is common to all two-lane, two-way highways regardless of locality and traffic level. This unique aspect of two-lane, two-way highways implies the use of freedom to pass as a service indicator to be a logical proposition.

Vehicle-Stratification Techniques

As PTSF is used as a performance measure for two-lane, two-way highways, any new analysis techniques need to relate vehicle platooning to the percent of time vehicles spend following other vehicles (PTSF). According to Luittenen (2002), the restriction on passing slower vehicles is the interaction most often perceived by motorists on two-lane, two-way highways. Conceptually, this means that slow-moving vehicles increase the need to pass, which in turn causes vehicle platooning. From this idea, two vehicle stratification techniques intended to represent PTSF were developed. Furthermore, when comprising these stratification techniques, ideas were taken from the analysis of the HCM 2000 procedure discussed in Chapter 3 and from Al-Kaisy and Durbin (2005).

From these ideas, it seems imperative that for any analytical technique to provide a realistic model of PTSF on two-lane, two-way highways, it should be able to segregate the two groups of vehicles that comprise vehicular platoons. As stated in Chapter 3, these two vehicle groups are:

1. Vehicles that travel voluntarily in a platoon at nearly their desired speed (same as platoon speed) while maintaining comfortable distance headway from the lead vehicle (shaded vehicles in Figure 6)
2. Vehicles that travel involuntarily in a platoon at less than their desired speeds, unable to pass slow-moving vehicles (white vehicles in Figure 6)

Separating vehicles into these two groups ensures that the technique will only estimate those vehicles that are driving at speeds slower than their individual desired speeds, or in other words, vehicles involuntarily traveling in a platoon being unable to pass slow-moving vehicles. The current study presents two new methods that are intended to stratify vehicles within a vehicular platoon into the two previously described vehicle groups. The two new methods are 1) weighted-average approach and 2) probabilistic approach.

First Proposed Method: Weighted-Average Approach

The first of the two new methods is aggregate in nature and utilizes a weighted average speed formula in estimating PTSF. The method is based on the premise that vehicle mix on two lane highways consists mainly of two groups of vehicles:

1. heavy vehicles (i.e. trucks, buses, and recreational vehicles (RV)) with relatively inferior performance and lower average speed

2. passenger cars (i.e. automobiles, SUVs, minivans, and other smaller vehicles) with relatively higher performance and higher average speed

While the speed differential between the two groups of vehicles is mainly induced by performance, it must be noted that the use of different legal speed limits could be another main contributor to speed differential. This proposed method employs two aggregate speed measures for each group of vehicles. Namely, the average actual travel speed of vehicles and the average desired travel speed of the vehicle drivers. Conceptually, the latter measure is always expected to be equal to or higher than the former measure. In the development of the weighted average approach, the following notations are used to refer to the different aggregate speed measures:

S_{apc}: Average actual travel speed of passenger cars
S_{ahv}: Average actual travel speed of heavy vehicles
S_{dpc}: Average desired travel speed of passenger cars
S_{dhv}: Average desired travel speed of heavy vehicles
S_{atot}: Average actual travel speed of all vehicles

As was mentioned previously, any method for determining PTSF needs to utilize the percentage of vehicles involuntarily traveling in platoons due to inability to pass as a surrogate measure to the PTSF. The weighted average approach accomplishes this by relating the average actual travel speed of all vehicles, S_{atot}, to the average actual travel speed of heavy vehicles and passenger cars in the traffic mix. Namely:

$$S_{atot} = P_{pc} S_{apc} + P_{hv} S_{ahv} \quad \text{Equation 4}$$

where,
P_{pc} = Proportion of passenger cars in the traffic mix
P_{hv} = Proportion of heavy vehicles in the traffic mix
S_{atot}, S_{dpc}, S_{ahv}, are as defined earlier

The proposed method further classifies heavy vehicles and passenger cars into two groups, i.e. those that are free to travel at their desired speeds and those that are involuntarily traveling in platoons. To segregate the two groups, Equation 4 can be modified as follows:

$$P_{pc} = P_{pc1} + P_{pc2} \quad \text{Equation 5}$$

$$P_{hv} = P_{hv1} + P_{hv2} \quad \text{Equation 6}$$

$$S_{atot} = \left[P_{pc1} S_{dpc} + P_{pc2} S_{tpc}\right] + \left[P_{hv1} S_{dhv} + P_{hv2} S_{thv}\right] \quad \text{Equation 7}$$

where,
P_{pc1} = Proportion of passenger cars traveling at desired speed
P_{pc2} = Proportion of passenger cars involuntarily traveling in platoons
P_{pc} = Proportion of passenger cars in the traffic mix
P_{hv} = Proportion of heavy vehicles in the traffic mix
P_{hv1} = Proportion of heavy vehicles traveling at desired speed
P_{hv2} = Proportion of heavy vehicles traveling involuntarily in platoons
S_{tpc} = Average speed of passenger cars traveling involuntarily in platoons
S_{thv} = Average speed of heavy vehicles traveling involuntarily in platoons
S_{atot}, S_{dpc}, S_{dhv}, are as defined earlier

It should be noted that P_{pc1} and P_{hv1} are the proportion of passenger cars and heavy vehicles, respectively, traveling at their desired speeds both within and outside platoons. Before continuing the development of the weighted average formula, an assumption was made to simplify the procedure. Namely, it was assumed that heavy vehicles are never impeded by passenger cars, while passenger cars may be impeded by heavy vehicles.

This assumption is largely consistent with the findings of a recent study (Polus et al. 1999) concerning various passing combinations of vehicles (i.e. passenger cars passing passenger cars, passenger cars passing trucks, etc.). The study investigated 1,500 passing maneuvers from six sites on tangent two-lane, two-way highways using video recoding and aerial photography. Results from the study showed no incidents of heavy vehicles passing passenger cars during any of the 1,500 observed passing maneuvers. However, the majority of passing maneuvers observed were passenger cars overtaking heavy vehicles.

Therefore, it can be assumed that heavy vehicles are generally not impeded by slower moving vehicles. From this assumption, it can be said that the average actual travel speed of heavy vehicles, S_{ahv}, is approximately equal to the average desired travel speed of heavy vehicles, S_{dhv}.

$$S_{ahv} \approx S_{dhv} \qquad \text{Equation 8}$$

Therefore, the second term of Equation 4 can be simplified as follows:

$$S_{atot} = \left[P_{pc1}S_{dpc} + P_{pc2}S_{tpc}\right] + \left[P_{hv}S_{ahv}\right] \qquad \text{Equation 9}$$

To further develop the weighted average model, Equation 9 was analyzed to determine which variables were obtainable in the field, and which were unattainable in the field. This is important as the method needs to be capable of estimating PTSF using field data. Variables determined to be obtainable in the field were:

S_{atot} = Average actual travel speed of all vehicles
S_{ahv} = Average actual travel speed of heavy vehicles
S_{dpc} = Average desired travel speed of passenger cars
P_{hv} = Proportion of heavy vehicles in the traffic mix

Of the above variables, S_{atot}, S_{ahv}, and P_{hv} can easily be determined in the field using traffic counting devices or methods that have the ability to classify vehicles. The last variable, S_{dpc} can be measured in the field using time headway and speed data (also obtained from traffic counting devices or methods). Specifically, passenger cars with time headways in excess of a certain cut-off value can be considered to be independent from platoons in the traffic stream, and thus their average speed represents the average desired speed of passenger cars.

As the above variables are measurable in the field, only three unknown variables remain from Equation 9, namely:

S_{tpc} = Average speed of passenger cars traveling involuntarily in platoons
P_{pc1} = Proportion of passenger cars traveling at desired speed
P_{pc2} = Proportion of passenger cars involuntarily traveling in platoons

In regard to these remaining unknowns, another assumption was made that the average speed of passenger cars traveling involuntarily in platoons is roughly equal to the average speed of the platoon leader, namely heavy vehicles. This is based on the before mentioned assumption that heavy vehicles are generally not impeded by passenger cars, while passenger cars may be impeded by heavy vehicles. Therefore, it can be assumed that the leaders of vehicle platoons are generally heavy vehicles and that the average speed of passenger cars traveling involuntarily in platoons is equal to the average travel speed of heavy vehicles. Consequently, the following equation was derived:

$$S_{tpc} \approx S_{apl} \approx S_{ahv} \qquad \text{Equation 10}$$

where, S_{apl} = Average travel speed of platoon leaders

S_{tpc} and S_{ahv} are as defined earlier

By substituting Equation 10 into Equation 9, the following equation results:

$$S_{atot} = \left[P_{pc1}S_{dpc} + P_{pc2}S_{ahv}\right] + \left[P_{hv}S_{ahv}\right] \qquad \text{Equation 11}$$

Further simplification of Equation 11 yields:

$$S_{atot} = \left[P_{pc1}S_{dpc}\right] + S_{ahv}\left[P_{hv} + P_{pc2}\right] \qquad \text{Equation 12}$$

Next, by rearranging Equation 5, $P_{pc} = P_{pc1} + P_{pc2}$, to read $P_{pc1} = P_{pc} - P_{pc2}$ and substituting this into Equation 12, Equation 13 results:

$$S_{atot} = \left[\left(P_{pc} - P_{pc2}\right)S_{dpc}\right] + S_{ahv}\left[P_{hv} + P_{pc2}\right] \qquad \text{Equation 13}$$

The final step in the formulation of the new model is to solve Equation 13 in terms of the variable P_{pc2}, the proportion of passenger cars traveling involuntarily in platoons.

$$P_{pc2} = \frac{S_{atot} - S_{dpc}P_{pc} - S_{ahv}P_{hv}}{S_{ahv} - S_{dpc}} \qquad \text{Equation 14}$$

As discussed in the opening of this chapter, the proportion of passenger cars involuntarily traveling in platoons at less than their desired speed is synonymous to percent time-spent-following. Thus, Equation 14 is the final representation of percent time-spent-following based on the weighted average vehicle stratification model.

Second Proposed Method: A Probabilistic Approach

Similar to the weighted-average approach, the second vehicle-stratification method utilizes a vehicle classification method to develop a model for relating vehicular platooning to PTSF. For the probabilistic approach, vehicles are classified as either slow-moving vehicles or fast-moving vehicles, regardless of vehicle size, performance, etc. For this method, these terms are defined as:

1. slow-moving vehicles – refers specifically to those vehicles that are (or potentially) leading platoons in the traffic stream. In other words, those vehicles that impede the flow of other vehicles in the traffic stream.
2. fast-moving vehicles – refers to those vehicles that are impeded by slow-moving vehicles and become part of platoons upon encountering slower vehicles in the traffic stream in the absence of passing opportunities (traveling involuntarily within the platoon).

The purpose of the probabilistic method is to determine a relationship between these two vehicle groups and the performance measure PTSF. This is accomplished by establishing two probabilities that are used in estimating PTSF. Those probabilities are:

- P_p = Probability of a vehicle being part of a vehicular platoon
- P_t = Probability of a vehicle traveling involuntarily in a platoon at a speed lower than the desired speed

<u>Determining the Probability P_p</u> P_p represents the probability that any car in the traffic stream will be traveling in a platoon, regardless of the driver's desire to be in the platoon. To establish the probability P_p, the proportion of vehicles that are part of platoons in the traffic stream needs to be estimated. This can be accomplished using vehicle time headway data. Specifically, vehicles are determined as part of a platoon by having time headways shorter than a pre-specified cut-off value while those outside platoons will

have time headways greater than the cut-off value. It should be noted, once again, that vehicular platoons involve vehicles that either involuntarily or voluntarily traveling within the platoon.

Determining the Probability P_t P_t represents the probability that vehicles are involuntarily traveling in a platoon at less than their desired speed due to the inability to pass. To determine the probability P_t, the proportion of vehicles traveling at speeds higher than the average speed of slow-moving vehicles needs to be determined. Vehicular speeds under free-flow conditions (i.e. desired speed) are often represented by the normal distribution.

By using the normal distribution to model the desired speed of passenger cars, the probabilistic method is based on the premise that vehicles with different desired speeds are spread randomly in the traffic stream. In other words, the distribution of desired speeds outside vehicular platoons is the same as that within vehicular platoons and is in turn, the same as the distribution of desired speeds for the overall traffic mix. Based on this premise, the probability that vehicles are involuntarily traveling in a platoon at less than their desired speed due to the inability to pass, P_t, can be determined by:

1. measuring the average speed of slow-moving vehicles
2. establishing the distribution of desired speeds for all vehicles in the traffic stream
3. determining the area under the normal distribution curve that represents vehicles with speeds higher than the average speed of slow-moving vehicles, P_t

As defined earlier, slow-moving vehicles refer to those vehicles that are leading platoons. Therefore, the first numbered item above can be achieved by obtaining vehicle time headway and speed data from traffic counting devices or methods which can be used to determine the average speed of vehicles leading platoons. Specifically, time headway can be used to identify platoon leaders while speed data can be used to estimate average speed. It should be noted that the proposition of platoon leaders being a representative sample of slow-moving vehicles is logical as the inability to pass slow-moving vehicles is the main cause of vehicular platooning. The second numbered item, distribution of desired speeds, can be established using speed measurements of vehicles traveling outside platoons. As described when determining P_p, those vehicles traveling outside platoons can be identified easily using vehicle time headway data.

The average speed of slow-moving vehicles along with the distribution of desired speeds can then be used to determine the percentage of vehicles traveling at speeds higher than the average speed of slow-moving vehicles. Specifically, the average speed of slow-moving vehicles can be used directly with the cumulative frequency distribution curve to find the required percentage (see Comments on New Methods at end of chapter for supplementary discussion). The percentage of vehicles traveling at speeds higher than the average speed of slow-moving vehicles can then be used to derive the probability P_t. Assuming a normal distribution for desired speeds of vehicles, P_t is represented in Figure 7.

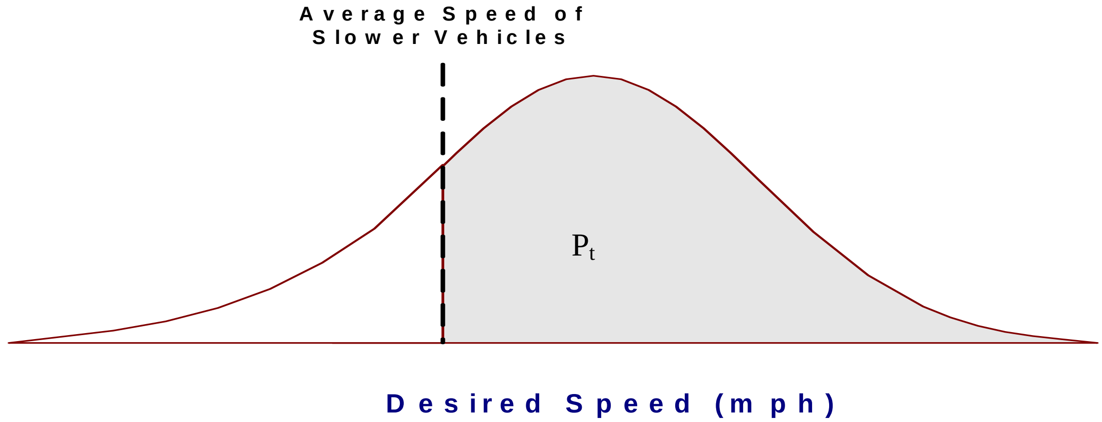

Figure 7 Theoretical Speed Distribution with Probability Pt Representation

Using the two probabilities described previously, PTSF can be estimated by applying the following equation:

$$PTSF = P_p \times P_t \qquad \text{Equation 15}$$

Therefore, Equation 15 is the final representation of percent time-spent-following based on the probabilistic vehicle stratification model.

Comments on New Methods

In practice, it is expected that for most situations the two stratification criteria utilized with the proposed new methods, 1) vehicle size for the weighted-average approach and 2) speed for the probabilistic approach, are related and may result in groups that largely overlap. This expectation is based on the premise that slow-moving vehicles hindering traffic are mostly heavy vehicles that generally exhibit inferior performance compared with smaller vehicles. Therefore, in cases with a high percentage of heavy vehicles, it is logical to expect that the two methods may result in a very similar PTSF value.

The proposed weighted-average method seems more appropriate when the traffic mix involves a relatively large proportion of heavy vehicles which normally constitute the vast majority of slow-moving vehicles. In this sense, the weighted-average approach has an inherent limitation. Namely, as the percentage of heavy vehicles becomes small, the accuracy of the PTSF estimation using the weighted-average approach may become an issue.

Theoretically, this method can be used with any vehicle mix regardless of the type of slow-moving vehicles and the percentage of heavy vehicles in the traffic stream. It becomes particularly appropriate when the percentage of heavy vehicles is relatively small or negligible and thus a larger portion of slow-moving vehicles is comprised of smaller vehicles.

Chapter Summary

This chapter discussed two new approaches for determining PTSF on two-lane, two-way highways, the weighted average and probabilistic approaches. In this regard, the chapter discussed the concepts and assumptions behind each method and outlined the formulation of equations intended to estimate PTSF based on the two methods. Also included in the chapter was a discussion of the platooning phenomenon and its implication on operational functionality of two-lane, two-way highways.

CHAPTER 5

TESTING NEW APPROACHES – DATA COLLECTION AND PROCESSING

This chapter discusses all the issues concerned with the collection and processing of the field data that was used to evaluate the proposed new methods discussed in the previous chapter. Specifically, the chapter discusses in detail the selection and description of study sites, data collection techniques, types of field data collected, and processing of field data into formats appropriate for analyses.

Selection of Study Sites

Three criteria were used in selecting the study sites. Specifically, study sites should, as much as possible, provide data that cover a wide range of traffic levels. In practice, traffic level is often expressed as a volume-to-capacity ratio. This is the ratio of the actual volume to the capacity of a particular facility and is either measured per direction or per lane. Volume counts published by the Montana Department of Transportation (MDT) and expressed in Average Annual Daily Traffic (AADT) on major highways in Montana along with the estimated capacity values were used to get an idea about the range of traffic conditions on various facilities throughout Montana. Furthermore, study sites should represent uninterrupted flow conditions away from the influence of driveways, intersections, or other access points that may have implications on vehicle speeds and behavior in the traffic stream. For practical reasons, study sites should be located at a reasonable proximity to Montana State University.

Description of Study Sites

Given the considerations discussed in the previous section, six directional study sites were selected at three different locations for this study. These site are listed below:

Study Site 1: Jackrabbit Lane near Four Corners, MT, Northbound
Study Site 2: Jackrabbit Lane near Four Corners, MT, Southbound
Study Site 3: Highway 287 near Three Forks, MT, Northbound
Study Site 4: Highway 287 near Three Forks, MT, Southbound
Study Site 5: Highway 287/12 near Townsend, MT, Northbound
Study Site 6: Highway 287/12 near Townsend, MT, Southbound

All highways chosen are classified as Class I highways according to the HCM 2000 highway classification. A map of study site locations can be seen in Figure 8.

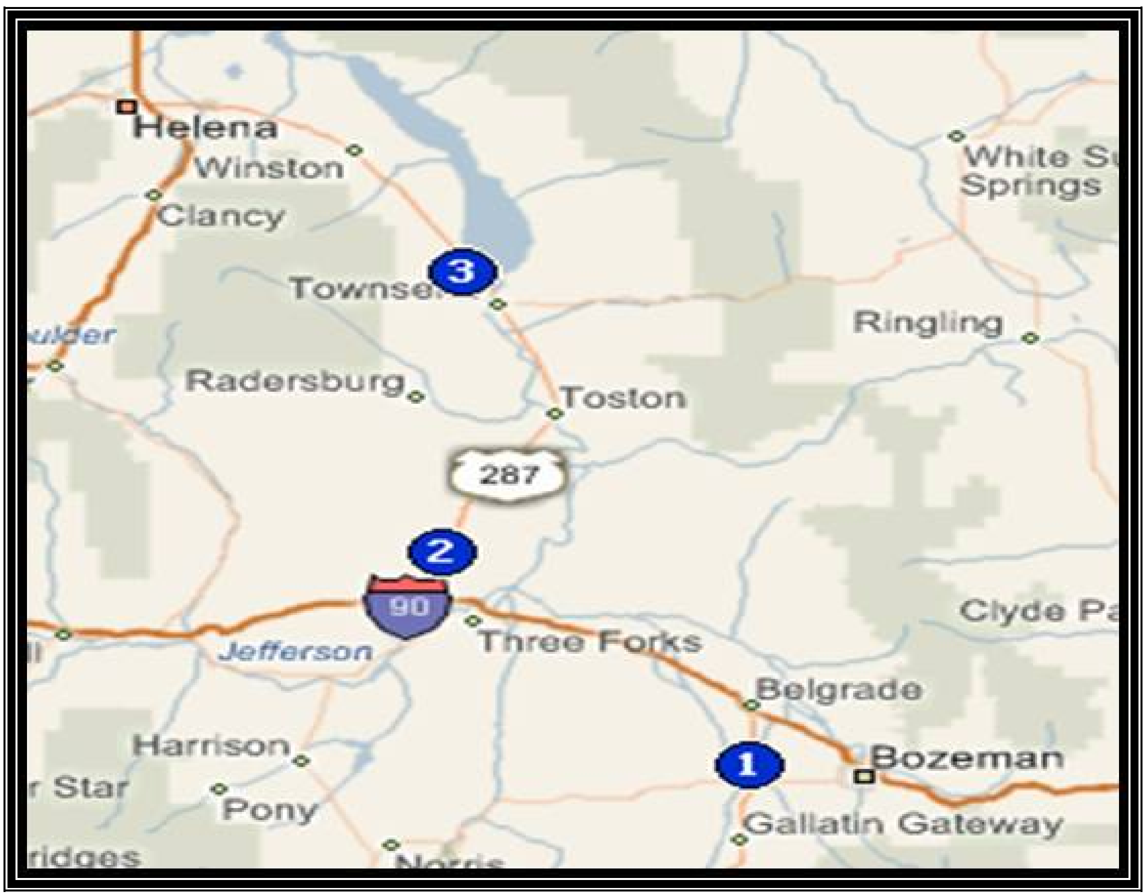

Figure 8 Map of Study Site (Microsoft)

Study Site 1 – Jackrabbit Lane

The first study site, Jackrabbit Lane, was chosen because it witnesses relatively high traffic volume according to the average annual daily traffic counts provided by the MDT. This segment of Jackrabbit Lane is a nearly 10-mile, two-lane, two-way highway section connecting Four Corners, MT and Belgrade, MT. Therefore, the segment is set in a rural/semi-urban environment and traverses level terrain. This highway segment is often used as a commuter route for people who live in the area of Belgrade, MT and work in the City of Bozeman, MT. The study sight location was chosen near the middle of this segment of Jackrabbit Lane in an attempt to reduce the effect of traffic control devices or other interruptions to traffic flow.

Study Site 2 – Highway 287

The second study site, Highway 287, was chosen because it experiences medium traffic volumes and is a long segment of highway away from any outside influences such as traffic control devices. Highway 287 is part of a route that connects Interstate 90 near Three Forks, MT to Interstate 15 at the Capitol of Montana, Helena. This particular segment extends for roughly 33 miles before intersecting with another major traffic corridor, Highway 12. This segment is in a rural setting with much of the roadway traversing rolling terrain.

Study Site 3 – Highway 287/12

The third study site, Highway 287/12, was chosen for reasons similar to those of study site 2. This is a 36 mile segment that runs from the junction of Highway 287 and Highway 12 in Townsend, MT to Helena, MT. Traffic increases along this route in the summer due to its location near three recreational lakes, which made it a promising location to analyze unique traffic mixes and traffic peaking characteristics. As with the previous study site, this segment is in a rural setting with much of the roadway traversing rolling terrain. It is important to note that this segment of Highway 287/12 contains a 2-mile passing lane about 2 miles north of the study site location, which has a direct impact on platooning for southbound traffic.

The percent no-passing zones and number of access points per mile for the study sites are provided in Table 5. The percent no-passing zones and number of access points per mile for the study sites were obtained from video and tabular highway records provided by the Montana Department of Transportation's Geometric Design Unit at Montana State University. These values are necessary for determining the PTSF based on the HCM 2000 two-lane, two-way analysis procedures. Also, the speed limit for all the study sites is 70 mph for passenger cars and 65 mph for heavy vehicles.

Table 5 Percent No-Passing Zones and Number of Access Points at Study Sites

	Northbound		**Southbound**		**Both Directions of Travel**		
Location	**Percent No Passing Zones**	**Accesses per Mile**	**Percent No Passing Zones**	**Accesses per Mile**	**Lane Width (ft)**	**Shoulder Width (ft)**	**Length of Segment (miles)**
Jackrabbit Lane	5.00	3.00	5.00	3.00	12.00	4.00	2.0
Highway 287	33.30	2.55	50.80	1.53	12.00	3.00	2.0
Highway 287/12	22.80	1.56	22.70	2.08	12.00	4.00	3.8

Data Collection Techniques

Equipment and Setup Procedures

Traffic data for this project was collected using TRAX I traffic pneumatic tube counters, a product of JAMAR Technologies, Inc. The TRAX I counter collects data in the following manner:

- Every time a vehicle passes over a road tube, a pulse of air is sent to the traffic counter and the counter records this pulse as a “hit”.
- For each “hit”, the instance in time in relation to the beginning of the data collection is recorded. This process is known as “time-stamping” the data.
- Each “hit” provides the recorder with an axle passage specific to every vehicle traveling on the roadway at the time it passed the counter.

Road tube installation was completed using the process outlined by Jamar Technologies and was set up using a configuration designed to collect time stamped data for two-lane, two-way highways (see Figure 9).

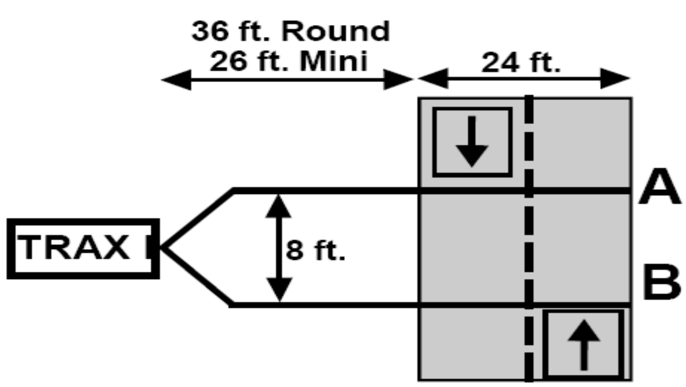

Figure 9 Road Tube Layout for Data Collection (Courtesy of Jamar Technologies, Inc.)

Description of Collected Data

Using the TRAX I traffic counters and the previously discussed installation procedures and configurations, data was collected from the various study sites. Table 6 shows the data collection dates, duration in hours and total observed vehicle counts from each study site.

Table 6 Description of Collected Traffic Data

	Northbound			Southbound		
Location	**Dates Collected**	**Collection Duration (hr)**	**Total Vehicle Count**	**Dates Collected**	**Collection Duration (hr)**	**Total Vehicle Count**
Highway 287	July 1, 2005 - July 4, 2005	81.90	8393	July 1, 2005 - July 4, 2005	81.90	7960
Highway 287/12	July 1, 2005 - July 2, 2005	20.75	2672	July 1, 2005 - July 2, 2005	20.75	2874
Jackrabbit Lane	July 31, 2005 - August 1, 2005	15.50	2128	July 31, 2005 - August 1, 2005	15.50	3491

As can be seen from Table 6, data was collected for no less than a 15-hour period, with a minimum of roughly 2000 vehicle observations. Furthermore, the data was collected during the summer months as to avoid the effects of poor road and/or weather conditions. After the data was collected, TraxPro computer software was used to process the time stamped data into per-vehicle information, which is discussed in the next section.

The installation procedures described previously allows for the determination of vehicle classification, individual vehicle speed, vehicle length, and time gap between successive vehicles in each direction of travel. Specifically, travel lane (direction of travel) is determined by setting the road tubes in a manner so that vehicles in one direction (southbound) would hit road tube A first while vehicles in the opposing direction (northbound) would hit road tube B first (see Figure 9). The vehicle would then pass over the following tube with the counter registering the hit.

Other traffic parameters were determined for individual vehicles using the same counter configuration. Namely, the time between consecutive hits and a predetermined distance (8 ft as shown in Figure 9) between the two road tubes that was set during installation are used to determine individual vehicle speeds, lengths, and time gaps between vehicles. Moreover, length of individual vehicles, or more specifically, length between the axles of a vehicle, was used to classify vehicles based on the American Association of State Highway and Transportation Officials' (AASHTO) vehicle classification system. This system has 13 different vehicle classifications that are as follows:

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

(See Appendix B for detailed description of the AASHTO vehicle classification system used in this research).

Data Processing

Before the data could be analyzed, the data output from the TraxPro computer software needed to be reviewed for any erroneous or irrelevant data. From this review, it was apparent that one of the classifications used by the software, the motorcycle classification, was irrelevant to the PTSF analysis that was to be completed using the data. Furthermore, a second classification, non-classified vehicles, which TRAXPro utilizes to represent data that were unrecognizable by the program was considered to be erroneous in nature. As these two vehicle classifications had no use in further analyses, they were removed from the processed data sets. Table 7 displays a breakdown of each data set based on vehicle counts for each of the AASHTO Classification 2-13 as well as overall vehicle counts.

Table 7 Vehicle Counts by AASHTO Classification for All Data Sets

	Study Site					
Vehicle Class	**Highway 287**		**Highway 287/12**		**Jackrabbit Lane**	
	NB	**SB**	**NB**	**SB**	**NB**	**SB**
2	4512	4443	1744	807	1009	1885
3	2324	2077	629	1146	655	882
4	60	40	10	39	24	12
5	634	590	114	525	254	468
6	17	28	11	11	27	34
7	0	1	0	3	3	9
8	657	633	99	290	87	103
9	158	107	44	38	31	55
10	9	11	5	2	15	27
11	2	1	1	1	2	0
12	5	5	1	4	1	1
13	15	24	14	8	20	15
All	8393	7960	2672	2874	2128	3491

NB = Northbound Traffic SB = Southbound Traffic

From Table 7, it is apparent that the majority of traffic using these facilities belongs to Class 2 and Class 3 vehicles, which represent passenger vehicles. Furthermore, the percentage of trucks using these facilities ranges from about 5 % to 25 % of the overall traffic mix, depending on the study site.

<u>Treatment of Traffic Peaking Characteristics</u>

One of the fundamental inputs in traffic analysis is the actual traffic volume on the roadway, usually expressed in vehicles per hour. Generally, the highest hourly volume in the 24-hour period, known as the peak-hour volume, is used for traffic analysis computations. This hourly volume needs to be adjusted to reflect the temporal variation of traffic demand within the analysis period, which is generally accomplished through the use of a peak hour factor (PHF). The PHF is “the hourly volume during the maximum-volume hour of the day divided by the peak 15-min flow rate within the peak hour; a measure of traffic demand fluctuation within the peak hour” (TRB 2000). PHF is determined using the following equation (Roess et al, 2000):

$$PHF = \frac{V}{4 * V_{m15}} \qquad \text{Equation 16}$$

where, PHF = peak hour factor
V = hourly volume, vehs
V_{m15} = maximum 15-minute period within the hour, vehs

PHF is one of the inputs needed to determine PTSF using the HCM 2000 method and was therefore calculated for each of the data sets.

In addition to the peak-hour volume, each of the six data sets was processed into a range of "peak time periods" in an effort to account for non-uniform arrival rates. Specifically, the following peak durations were used in the analysis

1. peak 15-minutes
2. peak 30-minutes
3. peak 45 minutes
4. peak hour
5. peak 2 hours

In the above intervals, "peak" refers to the largest volume of traffic experienced during the specified time interval. Table 8 displays the traffic volumes during each peak time period for the six data sets. Also, Table 8 displays the PHFs for the various study sites. According to the table, traffic volume is considerably higher for southbound traffic on Jackrabbit Lane during the peak time periods. Furthermore, the fluctuation in traffic, represented by the PHF, differs by study site. As Jackrabbit Lane is in a suburban setting, it is reasonable for this site to have a higher PHF than the other study sites that are in a more rural setting.

Table 8 Peak Traffic Volumes per Study Site

		Southbound Traffic			**Northbound Traffic**		
	Time Period Studied	**Highway 287**	**Highway 287/12**	**Jackrabbit Lane**	**Highway 287**	**Highway 287/12**	**Jackrabbit Lane**
Volume	**Peak 15 min**	98	104	217	73	83	89
	Peak 30 min	168	169	432	105	155	156
	Peak 45 min	227	246	618	154	230	232
	Peak hour	288	316	755	194	290	295
	Peak 2 hour	561	603	1345	352	561	580
	PHF	**0.73469**	**0.75962**	**0.86982**	**0.66438**	**0.87349**	**0.82865**

Chapter Summary

This chapter discussed the study site locations, data collection methods, and the type and amount of vehicular data collected for use in analyzing the new approaches discussed in Chapter 4. Moreover, the chapter outlined the vehicle classification techniques used in this research as well as the type of vehicle information that was obtained through data collection. Furthermore, the chapter covered some of the data processing that was essential in the analyses completed in the following chapters.

CHAPTER 6

PLATOONING ON TWO-LANE, TWO-WAY HIGHWAYS

As discussed in Chapter 4, the inability of two-lane, two-way highways to provide sufficient passing opportunities often leads to the formation of vehicle platoons. One of the main features of vehicular platooning is its affect on travel speed and vehicle headways. Specifically, vehicular platooning increases the proportion of vehicles with short headways and decreases mean travel speed. In an attempt to examine the affect of vehicle platooning on travel speed and vehicle headways, the following analyses were conducted.

Vehicle Headway versus Mean Travel Speed

This analysis is intended to analyze any relationships between vehicle headway and vehicle speed. Consequently, plots of headway versus mean travel speed were established for all the data sets discussed in Chapter 5. Specifically, the speeds of each individual vehicle were plotted against their corresponding headway. Headway values ranging from 1 to 8 seconds were analyzed to determine when, if ever, the speed of vehicles was no longer affected by headway. To ensure sample size would not affect the results, all data points from each of the six data sets were used to establish the graphs shown in Figure 10. No data set contained less than two thousand observations, which is sufficient to ensure sample size effects were minimal.

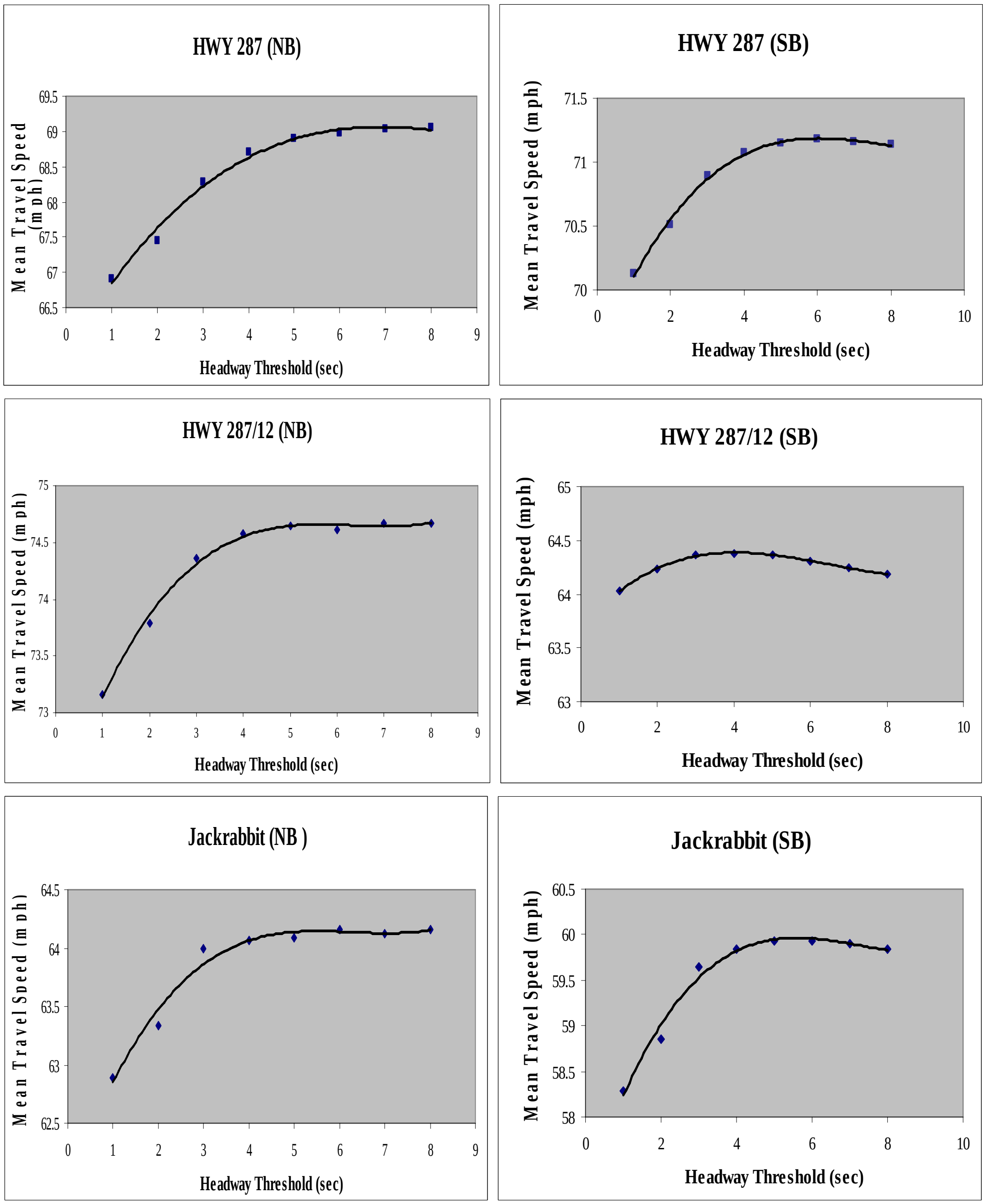

Figure 10 Speed versus Headway Threshold Value (sec)

Referring to Figure 10, a general trend or pattern can be discerned concerning the relationship between vehicle headway and mean travel speed. Specifically, mean travel speed of vehicles traveling at or greater than 1-second headways increases as the headway threshold value increases. This relationship holds until the headway value reaches roughly 5- or 6- seconds, where the vehicle speeds begin to flatten out as the headway threshold value increases. This means that at lower headway values (i.e. anything less than 6-seconds), there is a direct relationship between vehicle travel speed and time headway. This is consistent with the basic concept of most car-following theories, such as those discussed in Chapter 3.

As the headway threshold values become large (i.e. anything greater than 6- seconds), headway has little to no effect on vehicle travel speed. This relationship is expected, as larger headways means less interaction between vehicles with more vehicles traveling in free flow mode. Thus, at larger headways, vehicles are no longer hindered by each other and are therefore traveling close to their desired speeds.

To better assess the relationships shown in the previous figure, various curve types were fit to the data points. The best fit curve equations for travel speed in mph (y) and based on the headway threshold value in seconds (x) and the corresponding R-squared values between the two variables are provided in Table 9.

Table 9 Multiple Regression for Headway Threshold versus Travel Speed

Study Site	Best Fit	R Squared Value
Highway 287/12 (NB)	$y = 0.0105x^3 - 0.1997x^2 + 1.2504x + 72.075$	0.9946
Highway 287/12 (SB)	$y = 0.0037x^3 - 0.0723x^2 + 0.4039x + 63.691$	0.9974
Highway 287 (NB)	$y = 0.0041x^3 - 0.125x^2 + 1.1346x + 65.827$	0.9892
Highway 287/12 (SB)	$y = 0.004x^3 - 0.0946x^2 + 0.7081x + 69.487$	0.9964
Jackrabbit Lane (NB)	$y = 0.0093x^3 - 0.176x^2 + 1.0886x + 61.928$	0.9733
Jackrabbit Lane (SB)	$y = 0.0084x^3 - 0.1848x^2 + 1.2762x + 57.133$	0.9839

As can be seen from the table, the R-squared value between travel speed and headway threshold is at least extremely high for all study sites. This high relationship between the response variable, mean travel speed in miles per hour, and the predictor variable, headway in seconds, shows that travel speed on two-lane, two-way highways is considerably affected by the headway between consecutive vehicles traveling on the same lane. Furthermore, the relationship between these variables is apparently non-linear in nature, which is consistent with the previously discussed graphs from Figure 10. Again, this shows that speed and headway have a direct correlation at lower headways, but as headways increases, the relationship between speed and headway tends to diminish.

From the previous analyses, it would seem reasonable to establish a headway value that could be used to distinguish those vehicles that are indisputably traveling outside of vehicular platoons. As these vehicles represent those traveling in free-flow mode, it is plausible to use this as a cut-off value to establish desired speeds. Specifically, any vehicles traveling at headways larger than a specific cut-off value would be traveling in free flow mode without hindrance from other vehicles and thus traveling at their desired speed. As suggested by the headway versus mean travel speed curves in Figure 10, this headway cut-off value was conservatively estimated to be 6-seconds.

Platoon Size versus Mean Travel Speed

To understand the platooning phenomenon, it is essential to understand the relationship between vehicular platooning and the average operating speed of vehicles using two-lane two-way highways. The following analysis attempts to discern this relationship.

In this analysis, the average operating speed of all vehicles within vehicle platoons was established for each of the study sites. Furthermore, the analysis was completed for platoons of various sizes. According to the HCM 2000, a vehicular platoon is defined as a group of vehicles traveling together as a group, either voluntarily or involuntarily because of signal control, geometrics, or other factors (TRB 2000). Yet, the HCM 2000 suggests no particular number of vehicles that constitute a "group". However, the size of a platoon is deemed as a variable that could be used to distinguish between faster vehicles traveling with short headways (not impeded by slow-moving vehicles) and platoons formed by slow-moving vehicles which tend to be growing in size.

Therefore, the analysis was completed for platoons of size two, three, four, and five or more vehicles. Specifically, the first car in the group is known as the platoon leader, while all other cars traveling behind the platoon leader are simply referred to as platooned vehicles. As the HCM 2000 specifies three seconds to identify vehicles in platoons, this value was used to establish platooned versus non-platooned vehicles in this analysis. Once platoons were established, the average travel speed was determined for both the platoon leaders as well as the vehicles within the platoons. Figure 11 displays the results from the analysis for the six study sites. It should be noted that the average speed of vehicles within the platoon doesn't include the speeds of the platoon leaders. However, the size of platoons on the x-axis includes the platoon leader and any vehicles following the platoon leader.

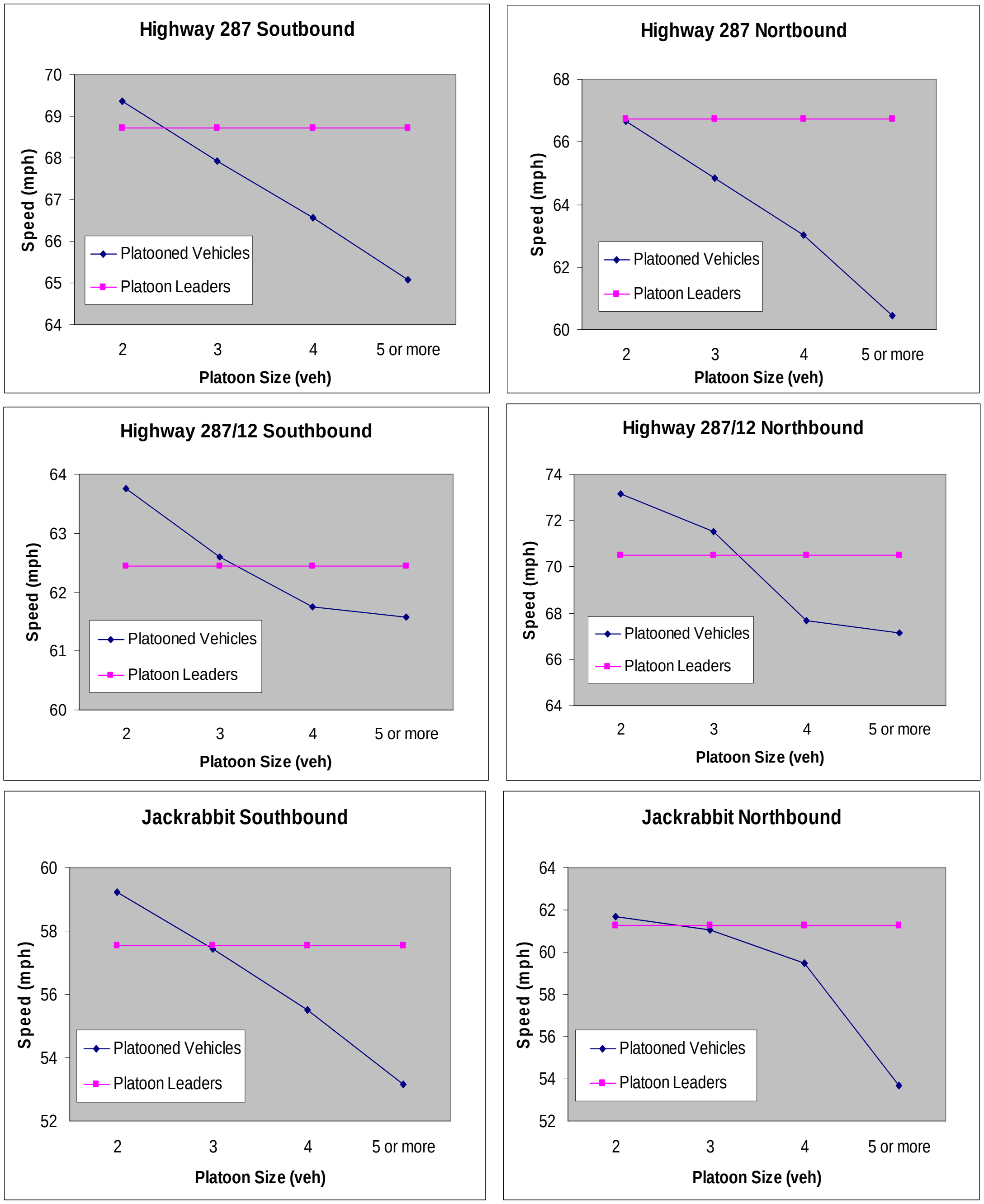

Figure 11 Average Speed of Various Sized Platoons by Study Site

The values in Figure 11 represent all data from each of the study sites, i.e., all the graphs were developed using no less than two thousand observations. It is clearly shown in Figure 11 that as the number of vehicles in a platoon increases, the mean travel speed of the platoon decreases. This pattern is consistent with expectations based on the understanding of the platooning phenomenon on two-lane highways. The figure also provides much needed insight into the nature of a platoon in regard to the impedance to traffic by slow-moving vehicles and the number of vehicles within the platoons. Specifically, this figure suggests that as platoon size increases, the likelihood of platoons forming from the impedance of slow-moving vehicles increases.

Chapter Summary

This chapter involved two important analyses that are related to the platooning phenomenon on two-lane highways. In particular, the analyses investigated the relationships between time headway and average travel speed and between platoon size and average travel speed. From these analyses, two major trends were established.

First, vehicle travel speeds have a direct relationship with time headway. Specifically, average travel speed increases steadily with the increase in time headway. However, vehicle headway tends to have a little effect on vehicle travel speed as the headway value exceeds six seconds. Second, as the number of vehicles within a platoon increases, the mean travel speed of the platoon decreases. This is consistent with the idea that as more vehicles use the roadway, interaction between vehicles will increase and in turn, travel speeds will decrease (due in large part to safety considerations/concerns of drivers). Furthermore, it was shown that the correlation between vehicle headway in seconds and speed in mile per hour is strong.

These results are consistent with traffic flow principles in that smaller headways mean more vehicle interactions and lower speeds, whereas larger headways mean little vehicular interaction and higher speeds. From these analyses, it is reasonable to assume that a vehicle headway of greater than five or six seconds can be used to establish platooned vehicles as there is little vehicular interaction (if any) beyond this point. For analysis purposes later in this research, a conservative value of six second headways will be used to separate platooned from non-platooned vehicles in the traffic stream.

CHAPTER 7

TESTING NEW APPROACHES – WEIGHTED AVERAGE APPROACH

The current chapter validates the weighted average approach for measuring PTSF using the data described in Chapter 5. The chapter begins with a discussion of the vehicle grouping schemes used to analyze the proposed approach followed by an evaluation of traffic peaking characteristics and its effect on PTSF. The chapter ends with a discussion of particular variables that affect the PTSF results from the weighted average approaches.

Empirical Validation of Proposed Approach

As discussed in chapter 4, the weighted average approach is aggregate in nature and is based on the premise that vehicle mix on two lane highways consists mainly of two groups of vehicles: passenger cars and heavy vehicles. Specifically, heavy vehicles represent slow-moving vehicles that hinder the travel of fast-moving vehicles, which are generally represented as passenger cars. The first step in analyzing the weighted average approach was to establish which vehicles in the traffic stream are passenger cars and which are heavy vehicles.

As Chapter 5 outlined, TRAX I counters used for data collection classified vehicles via the AASHTO vehicle classification system. This system consists of 13 different vehicle types, 12 of which were used in the data analysis, with motorcycles (Class 1) being the excluded. Diagrams of the various classifications can be seen in Appendix B.

Upon initial inspection of the AASHTO vehicle classification system, the 12 classes were separated as Classes 2 and 3 belonging to the "passenger cars" category, while the rest were considered "heavy vehicles." As the approach utilizes the speed of vehicles in estimating the PTSF, it was critical to separate vehicles by performance and not only by AASHTO classification that is primarily based on vehicle dimensions. Failing to do so may compromise the accuracy of the proposed procedure. To that end, it was decided to analyze travel speeds of various AASHTO vehicle classes to reach the most appropriate way in segregating the two categories of vehicles.

Accordingly, the average free flow speed for each of the 12 vehicle classifications was measured at each study site. The free flow speeds were determined by sorting out those vehicles in free-flow mode using time headway information. Specifically, a headway threshold value of eight seconds was used to identify vehicles traveling at their desired speeds (threshold value was derived from the analyses included in chapter 6). This headway value was chosen as a conservative measure to establish vehicles that are traveling at their desired free-flow speeds, well outside of any influence from other vehicles.

The average free-flow speeds for various vehicle classes are shown in Table 10. This table shows that the free flow speeds of a few of the vehicles previously classified as "heavy vehicles" (i.e. AASHTO classes 4-13) are as high or higher than the average travel speeds of vehicle previously classified as "passenger cars" (i.e. AASHTO classes 2 and 3). Therefore, it seems that the performance of vehicles may be a more appropriate means to categorize their role in the formation of platoons.

Table 10 Average Vehicle Speed (mph) Categorized by AASHTO Vehicle Classification

Vehicle Class	Northbound Traffic					
	Highway 287 South		Highway 287 North		Jackrabbit Lane	
	Speed (mph)	Count (veh)	Speed (mph)	Count (veh)	Speed (mph)	Count (veh)
2	72.20	2767	64.71	903	64.57	567
3	71.29	1413	64.00	318	64.55	361
4	66.87	45	59.00	5	63.47	17
5	71.01	405	63.59	68	64.50	145
6	65.88	8	59.38	8	61.53	15
7	0.00	0	0.00	0	60.33	3
8	67.80	469	60.97	63	62.16	63
9	64.13	128	59.03	38	60.11	27
10	65.25	8	59.20	5	59.40	10
11	70.50	2	54.00	1	59.50	2
12	64.00	5	58.00	1	55.00	1
13	64.83	12	58.45	11	60.44	18

Vehicle Class	Southbound Traffic					
	Highway 287 South		Highway 287 North		Jackrabbit Lane	
	Speed (mph)	Count (veh)	Speed (mph)	Count (veh)	Speed (mph)	Count (veh)
2	69.99	2202	74.53	387	59.94	718
3	69.05	1135	76.32	632	60.86	373
4	62.64	28	68.61	28	55.30	10
5	69.26	329	75.35	297	60.65	173
6	65.00	13	67.25	8	56.86	22
7	62.00	1	77.50	2	56.75	4
8	65.67	399	70.73	194	57.81	59
9	61.98	86	67.24	29	56.80	44
10	61.33	9	69.00	2	56.94	16
11	71.00	1	73.00	1	0.00	0
12	56.33	3	69.33	3	56.00	1
13	59.90	20	68.50	8	57.00	9

When analyzing by performance, it is imperative that the number of observations for each classification be considered. Therefore, what really matters are those vehicles that exhibited high performance (as indicated by speed) based on a reasonably large number of vehicles. Using average free-flow speed of a small number of vehicles may be misleading when used in segregating the two categories of vehicles. In summary, it is apparent from the previous discussion that it is more accurate to use vehicle performance in establishing the two groups of vehicles as opposed to strictly using the AASHTO dimensional vehicle classification.

Examination of Vehicle Grouping Schemes

Based on the above discussion, four vehicle grouping schemes were examined based on either the AASHTO dimensional classification (passenger cars versus trucks/buses) or vehicle performance as evidenced by the analysis of free-flow speeds, namely:

1) AASHTO Classes 2 and 3 were categorized as group I (small/high performance vehicles), while other Classes (4-13) were categorized as group II (heavy vehicles/low performance).
2) AASHTO Classes 2, 3, and 5 were categorized as group I, while other Classes (4-13) were categorized as group II.
3) AASHTO Classes 1-6 were categorized as group I, while Classes 7-13 were categorized as group II.
4) AASHTO Classes 2 and 3 were categorized as group I and Classes 7–13 were categorized as group II with Classes 4-6 excluded from the analysis.

Based on the description of the AASHTO vehicle classes, the first grouping scheme partitions all passenger cars into the high performance group and all heavy vehicles into the low performance group.

The second scheme considered Class 5 as high performance rather than low performance vehicles. As can be seen in Table 10, the average free flow speed of Class 5 is one of the highest among all vehicle classes.

The third scheme is based on the premise that the average free flow speeds of vehicles in Classes 2 through 6 were considerably higher than the average free flow speeds of the remaining classes. Therefore, under this scheme, the high performance vehicle classification used for analysis was comprised of vehicle Classes 2-6 while the low performance vehicle classification was comprised of vehicle Classes 7-13.

The fourth and final scheme is based on the premise that some vehicle classes exhibited moderate performance at various study sites and therefore they are not clear cut as to be included in either of the groups. It was deemed both interesting and instructive to see how the exclusion of those groups would affect the accuracy of the weighted average approach.

Table 11 displays the PTSF values from the weighted average approach using the previously mentioned grouping schemes for each of the peak time periods discussed in Chapter 5. Upon review of Table 11, some of the PTSF values obtained from the analysis are physically impossible to realize. Specifically, as PTSF is a percentage, it is not possible to have a PTSF value outside the range of 0 to 100 percent.

Therefore, any values that fall outside of this range have been distinguished by grey boxes and either bold or italicized lettering. Italicized values represent PTSF values that are negative in magnitude, while bolded values represent PTSF values that are above 100 percent. As these results are not possible based on the definition of percentage, it is apparent that there are potential limitations within the weighted average approach that could occur from flawed data. The following discusses these potential problems within the weighted average approach.

Table 11 PTSF Values for Weighted Average Analysis

Analysis		**Northbound Traffic**			**Southbound Traffic**		
Class System	Time Period Studied	Highway 287	Highway 287/12	Jackrabbit	Highway 287	Highway 287/12	Jackrabbit
1	Peak 15 min	**117.53**	31.32	**277.33**	179.05	24.22	4.72
	Peak 30 min	94.48	30.43	**245.80**	72.00	35.93	34.19
	Peak 45 min	85.54	32.86	**105.75**	62.22	21.60	49.17
	Peak hour	65.06	31.84	**107.62**	52.97	17.46	56.72
	Peak 2 hour	55.37	26.81	92.47	30.48	3.36	65.18
2	Peak 15 min	**147.70**	44.90	80.31	36.27	25.95	2.17
	Peak 30 min	90.23	42.11	70.55	30.75	35.34	31.25
	Peak 45 min	76.69	38.82	48.81	30.26	27.89	33.41
	Peak hour	55.99	38.94	37.62	28.08	22.10	45.77
	Peak 2 hour	48.01	27.69	38.46	23.95	7.21	49.03
3	Peak 15 min	**147.70**	42.17	80.31	43.23	25.12	2.17
	Peak 30 min	**113.35**	43.25	62.02	34.78	36.40	28.47
	Peak 45 min	93.70	40.50	46.61	37.04	28.08	30.67
	Peak hour	68.73	42.66	33.48	35.73	21.04	44.47
	Peak 2 hour	57.39	32.94	37.09	25.10	8.52	48.12
4	Peak 15 min	**149.19**	32.53	93.41	51.83	23.68	*-0.62*
	Peak 30 min	**114.81**	33.05	75.48	38.46	35.21	23.92
	Peak 45 min	94.77	33.67	52.87	40.46	24.25	29.44
	Peak hour	68.81	34.96	43.10	43.39	17.68	42.77
	Peak 2 hour	56.88	27.13	42.40	26.04	3.71	47.74

Limitation 1 PTSF values at or below 0% result from the weighted average method when the percentage of low performance vehicles within the traffic stream approaches zero. As the percentage of low performance vehicles approaches zero, the percentage of high performance vehicles will approach 100%, which increases the effect of free flow speed of high performance vehicles on the PTSF value.

Consequently, if the percentage of low performance vehicles is negligible and the free flow speed of high performance vehicles is considerably higher than the average travel speed of the overall traffic mix, the weighted average approach could result in negative PTSF values. Therefore, the weighted average approach is inaccurate for determining PTSF on highways where low performance traffic, mainly heavy vehicles, is scarce.

Limitation 2 PTSF values above 100% can result from the weighted average method when the average travel speed of low performance vehicles, usually heavy vehicles, is higher than the speed of the overall traffic mix. This is one of the major concerns with the weighted average method and is the idea behind classifying vehicles as high and low performance rather than as passenger cars and heavy vehicles.

In regard to the previous discussion, these limitations are more of a concern of flawed or inadequate data than flaws of the weighted average concept. Consequently, any data used to establish PTSF based on the weighted average approaches needs to consider sample size and percentage of heavy vehicles within the traffic stream.

An analysis of the four grouping schemes shows that the occurrence of PTSF values outside of the range of 0 to 100% is less for vehicle classification methods 2 and 3 (3 of 60 PTSF values, 5%) than for methods 1 and 4 (9 of 60 PTSF values, 15%). For this reason, it is the suggestion of this research that vehicle classification schemes 1 and 4 be omitted from any further analysis.

Of the remaining two schemes, scheme 2 appears to be more promising. To strengthen this idea, one simply needs to look at the average free flow speeds presented in Table 10. The speed of Class 5 vehicles is generally near the speed of Class 2 and 3 vehicles, which are passenger vehicles. Furthermore, Class 4 and Class 6-13 are similar in free flow speeds. Therefore, it would seem more appropriate to group Classes 2, 3 and 5 as high performance vehicles and the rest of classes as low performance.

Another reason to use this scheme is that it is more consistent with methods used by the HCM 2000. Specifically, the HCM 2000 procedures separate Class 5, RVs, from the rest of the heavy vehicle class (i.e. Class 4, buses, and Class 6-13, trucks). As grouping scheme 2 uses the same partitioning, it would seem plausible to utilize this scheme over the others. Consequently, only vehicle scheme 2 will be retained for further analysis.

Examination of Traffic Peaking and Heavy Vehicle Percentage

The purpose of the analysis discussed in this section is to investigate two variables that potentially have an effect on PTSF values from the weighted average approach. These variables are 1) traffic peaking characteristics and 2) the percentage of heavy vehicles in the traffic stream.

To investigate the effect of these variables on PTSF results from the weighted average approach, PTSF as a function of peak time period has been compared against the percentage of heavy vehicles and a value meant to depict traffic peaking called the traffic intensity ratio, TIR. The traffic intensity ratio is a term established for this research and is defined as the volume during the maximum-volume time period of the day divided by the peak 15-min flow rate within that time period. The TIR is a measure of fluctuation of traffic within the peak time period and is determined by:

$$TIR = \frac{V_i}{V_{15} R} \qquad \text{Equation 17}$$

where V_i = volume for the ith time period (veh/time)
V_{15} = volume for peak 15 minute time period
R = ratio where R = ith time period (minutes)/15 minutes

For example, the peak 30 minutes and peak 15 minute volumes for southbound traffic from the Highway 287 study site are V_{30} = 105 veh/30-minutes and V_{15} = 63 veh/15-minutes. Furthermore, the ratio of 15 minutes to 30 minutes is 2 (i.e. R = 15/30 = 2). The corresponding TIR ratio for this example would be:

$$TIR = \frac{105}{63 * 2} = 0.8\overline{33}$$

It should be noted that volume, one of the variables effecting PTSF, is inherently represented within the TIR. Therefore, volume was left out of the analysis to avoid redundancy. Figure 12 displays the plots of PTSF as a function of percentage of heavy vehicles and the TIR for all six data sets discussed in Chapter 5. Referring to the figure, PTSF and percent heavy vehicles has been plotted on the left y-axis, while the TIR has been plotted on the right y-axis.

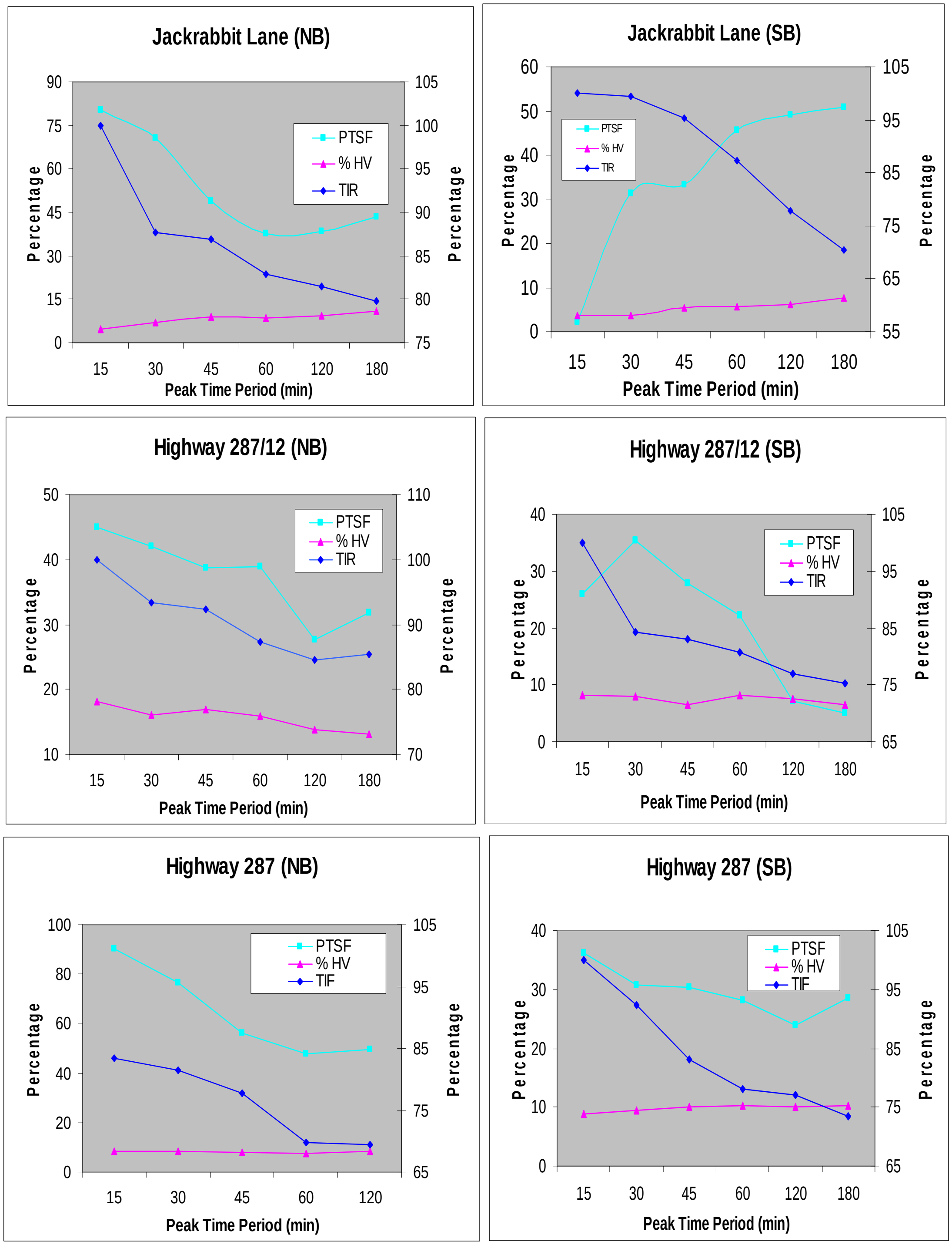

Figure 12 Heavy vehicle, TIF, and PTSF versus Time for Weighted Average Approach

Referring to Figure 12, a direct relationship between PTSF and the TIR can be established. For example, the plot for northbound traffic on the Highway 287 study site shows a steady decrease in the TIR as time increases (see duplicate of plot in Figure 13). Likewise, the PTSF values follow a similar pattern. Furthermore, as heavy vehicle traffic is nearly constant in the graph, the change in PTSF would appear to be due entirely to the change in the TIR. Similar trends can be seen with all data except for southbound traffic on Jackrabbit Lane, which will be discussed in a later section.

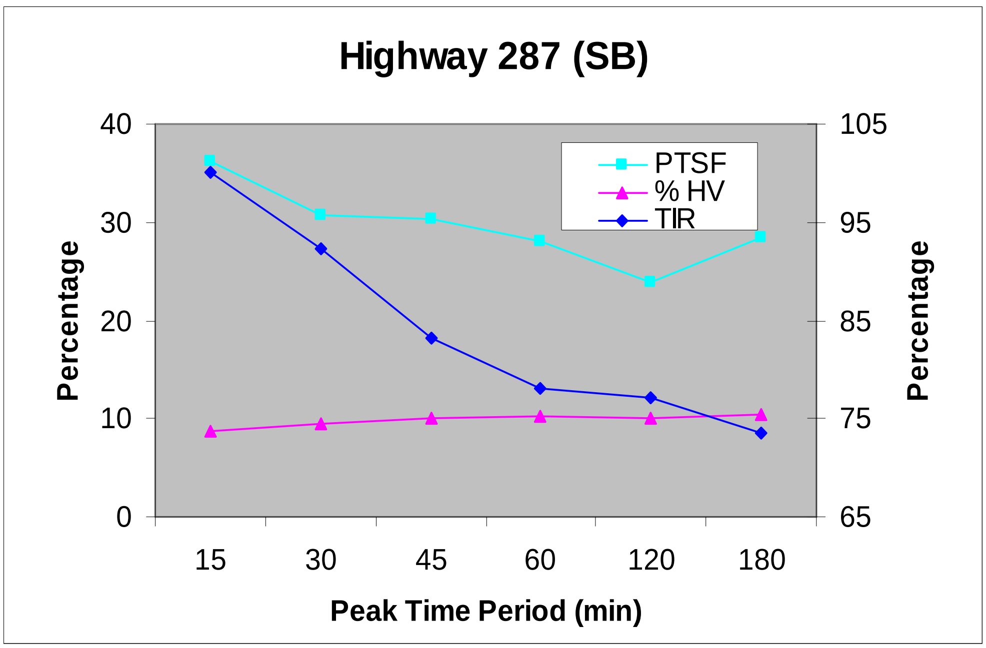

Figure 13 Heavy vehicle, TIR, and PTSF versus Time for Highway 287 Northbound

As TIR is a representation of traffic peaking characteristics, a relationship can be drawn between this phenomenon of traffic operation and PTSF results from the weighted average approach. Namely, as traffic peaking decreases, PTSF results from the weighted average approach will consequently decrease and vice-versa. Exceptions to the pattern seem to be the effect of the percentage of heavy vehicles within the traffic stream, which is discussed in the following section.

Referring to Figure 12, a trend can be seen in regard to the effect percentage of heavy vehicles in the traffic stream has on the PTSF results from the weighted average approach. Conceptually, a larger percentage of heavy vehicle traffic in the traffic stream should be reflected by more vehicle platooning and hence higher PTSF values. The data reflects this idea as PTSF shows a direct relationship to the percentage of heavy vehicle traffic. For example, the plot for northbound traffic on Jackrabbit Lane shows a steady increase in heavy vehicle traffic over time (see duplicate of plot in Figure 14).

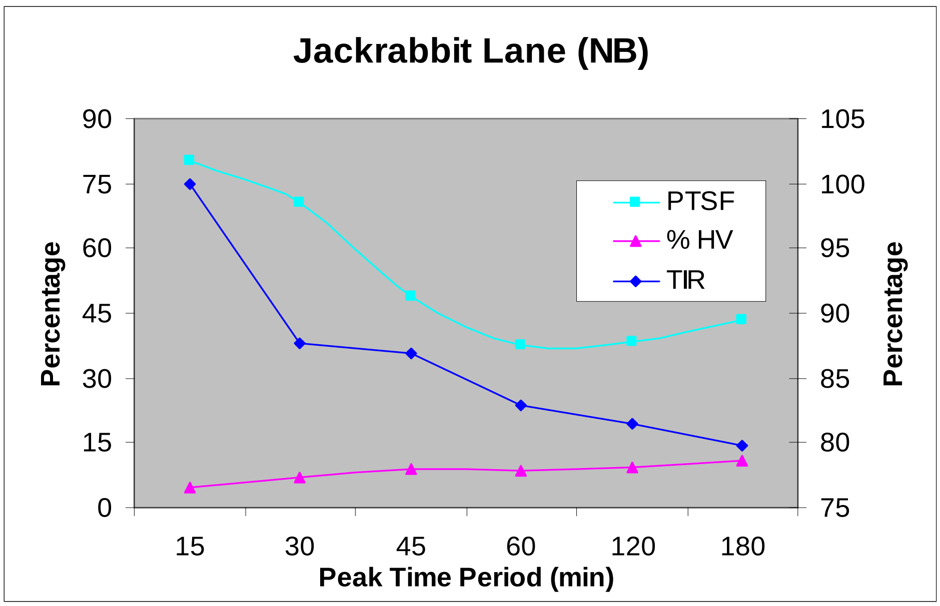

Figure 14 Heavy vehicle, TIF, and PTSF versus Time for Jackrabbit Lane Northbound

PTSF values on this graph decrease at first, but the pattern reverses toward the later time periods. This would appear to be an effect of increasing heavy vehicle traffic on the road in comparison to little to no change in the traffic volume represented by the TIR. Similar trends can be discerned from plots for the other study sites. Consequently, it would appear that PTSF values increase in response to the steady increase in heavy vehicle traffic and vice-versa.

To analyze the combined effect of these two variables, the data for southbound traffic on Jackrabbit Lane will be analyzed. The data for southbound traffic on Jackrabbit Lane from Figure 12 has been duplicated in Figure 15.

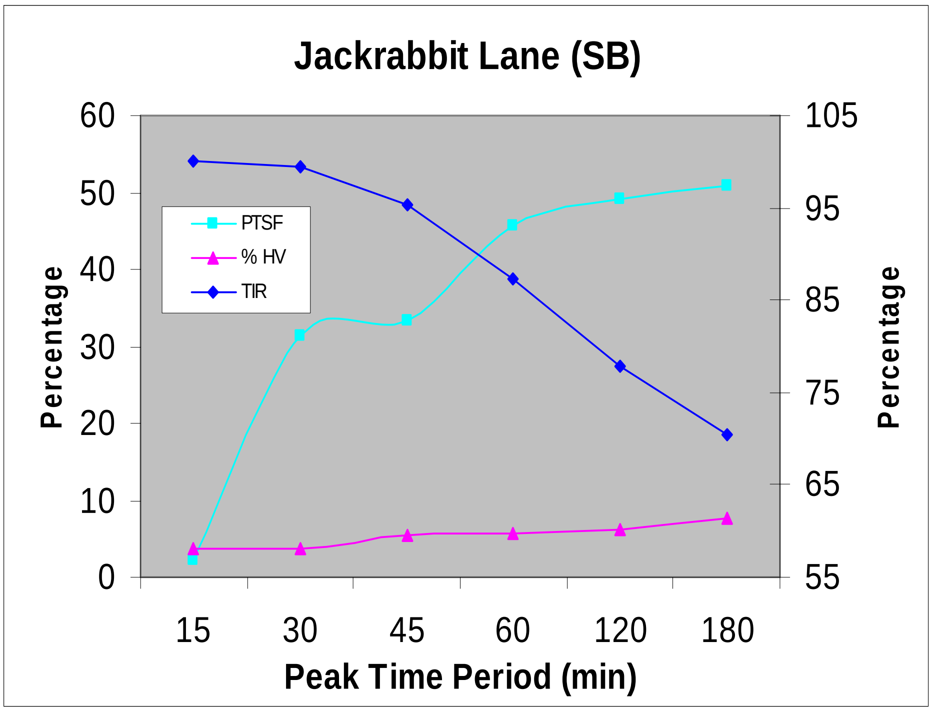

Figure 15 Heavy vehicle, TIF, and PTSF versus Time for Jackrabbit Lane Southbound

Referring to Figure 15, Jackrabbit Lane experiences little to no decrease in traffic volume during the first half an hour. Also, the heavy vehicle traffic during this time increased by about 2% and the patterns seen in the plot show that PTSF consequently increases at a rapid rate. However, after the first half an hour, traffic volume begins to decline at a steady pace, yet heavy vehicle is still increasing. This effect is reflected by the PTSF results as values in the plot still increase due to the increase in heavy vehicle traffic, yet the slope is less due to the decreasing traffic volume.

To investigate the correlation between the two predictor variables, the percentage of heavy vehicles and the TIR, and PTSF result from the weighted average approach, a multiple linear regression analysis was completed in Microsoft Excel. The prediction equations and R Squared values corresponding to each study site are shown in Table 12. Regression outputs can be seen in Appendix C.

According to the table, the results show that the majority of variability in PTSF values can be attributed to the combined effect of the percentage of heavy vehicles and the TIR. The rest of the variance in PTSF is due to random fluctuation. With the exception of southbound traffic on Highway 287/12, the R Squared values are all above 0.60, which is significant. However, as Highway 287/12 has a passing lane 2 miles upstream, which has a large effect on platooning and thus PTSF, the results are expected. Therefore, it would seem that the weighted average approach is effectively capturing PTSF values based on other variables such as the percentage of heavy vehicles, traffic peaking, and passing lanes.

Table 12 Multiple Regression for Weighted Average Approach

Study Site	Linear Regression Model	R Squared
Highway 287 (NB)	PTSF = -130.230 + -5.0483 (%HV) + 3.087 (TIR)	0.9644
Highway 287 (SB)	PTSF = -34.391 + 2.477 (%HV) + 0.472 (TIR)	0.7411
Highway 287/12 (NB)	PTSF = -30.987 + 1.807 (%HV) + 0.443 (TIR)	0.8452
Highway 287/12 (SB)	PTSF = -50.534+ 1.487 (%HV) + 0.720 (TIR)	0.3403
Jackrabbit Lane (NB)	PTSF = -61.062 + -2.236 (%HV) + 1.534 (TIR)	0.7910
Jackrabbit Lane (SB)	PTSF = 19.547 + 7.466 (%HV) + -0.277 (TIR)	0.6600

Chapter Summary

This chapter validates the concept of the weighted-average approach using empirical data. Specifically, field data was used to test various vehicle grouping schemes using AASHTO vehicle classifications produced by automatic traffic counters. Furthermore, the chapter looked at the effect of traffic level and heavy vehicle traffic on PTSF results. The following discusses the major findings of these investigations.

First, results from the vehicle stratification analysis show that performance is a better stratification criterion than vehicle class. In other words, a vehicular class may be described as "heavy vehicle" but in reality its performance is comparable to smaller vehicles. Four grouping schemes were tested and the vehicle grouping scheme in which Class 2, 3, and 5 vehicles were considered as smaller (high performance) vehicles and Class 4, and 6-13 vehicles as heavy (low performance) vehicles, yielded the best results.

The second important observation is that the majority of results that are inconsistent with the understanding of the PTSF performance measure occur for short time intervals. As short time intervals have considerably less observations than long time intervals, it is apparent that sample size has an effect on the PTSF results from the weighted average approach. As this method is dependent on average speeds of vehicles, the sample size needs to be large enough to provide a representative sample of the traffic mix. For this reason, a time interval of at least one full hour (typically peak hour) should be used in estimating the PTSF.

Finally, the regression analysis showed that the PTSF values resulting from the weighted average method are greatly affected by the percentage of heavy vehicles and traffic level. This is important as these two variables should have a direct effect on platooning and thus on the PTSF.

CHAPTER 8

TESTING NEW APPROACHES – PROBABILISTIC APPROACH

As mentioned in Chapter 4, the probabilistic method used to determine PTSF on two-lane, two-way highways is concerned with two probabilities. They are the probability of a vehicle being part of a vehicular platoon, P_p, and the probability of a vehicle traveling involuntarily in a platoon at a speed lower than its desired speed, P_t. This chapter looks at establishing these probabilities, and in-turn PTSF, using vehicle headways from the six data sets discussed in Chapter 5.

Empirical Validation of Proposed Approach

Determining the Probability P_p

To determine the probability of a vehicle being part of a vehicular platoon, P_p, the data was first separated into vehicles traveling within platoons and those vehicles traveling outside of platoons. To accomplish this, vehicles with time headways shorter than a pre-specified cut-off value were categorized as part of a platoon while those outside platoons have time headways greater than the cut-off value. A pre-specified cut-off value of six seconds was used in accordance with results from the analyses discussed in Chapter 6.

After platooned and non-platooned vehicles were separated using the method described above, the probability P_p was determined by simply dividing the number of vehicles traveling within platoons by the total number of vehicles. The result was the proportion of vehicles within the traffic stream that were traveling in platoons according to the specific headway cut-off value.

Determining the Probability P_t

To determine the probability of a vehicle traveling involuntarily in a platoon at a speed lower than their desired speed, P_t, a means for separating vehicles within the platoon was needed. This was accomplished by first determining the distribution of desired speeds for all vehicles within the traffic stream. Next, the average speed of all vehicles traveling in platoons was established. This value was used to separate those vehicles traveling involuntarily in platoons from those vehicles traveling voluntarily in platoons.

Specifically, the proportion of vehicles traveling involuntarily within platoons was established by finding the area under the curve representing vehicles with desired speeds greater than the average speed of vehicle platoons. This area was then divided by the total area under the curve, to give the proportion of vehicles traveling involuntarily within platoons.

After the probabilities P_p and P_t were determined, the PTSF according to the probabilistic method was found by simply multiplying these two probabilities together and converting to percentage. The following sections discuss various analyses that were performed using the probabilistic method, beginning with the investigation of traffic peaking characteristics and its effect on PTSF results.

Analysis of Traffic Peaking Characteristics

As was mentioned in Chapter 5, the data collected from the study sites was processed using various peak time periods, namely; peak 15 minutes, peak 30 minutes, peak 45 minutes, peak hour, and peak 2 hours. The method discussed previously for determining PTSF based on the probabilistic method was carried out for each of these time intervals. The PTSF value as a function of analysis duration in minutes at various study sites is shown in Figure 16.

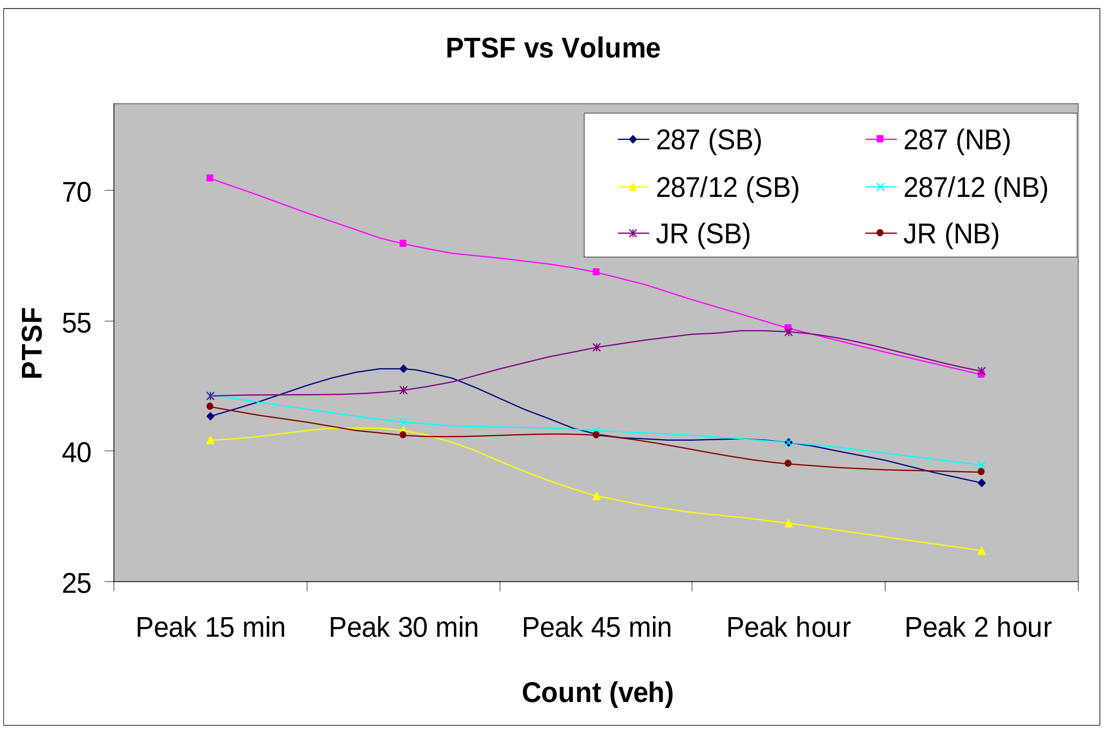

Figure 16 PTSF Values for Peak Time Periods

As mentioned earlier, a headway cut-off value of 6 seconds was used to establish the probability P_p in the calculation of PTSF. The use of a headway cut-off value of six seconds was based on the analysis of time headway versus speed discussed in Chapter 6.

In Figure 16, the NB and SB in the key represent northbound and southbound traffic for each of the study sites. Furthermore, JR represent study site 1: Jackrabbit Lane, 287 represents study site 2: Highway 287, and 287/12 represents study site 3: Highway 287/12.

Referring to Figure 16, reasonable patterns exist between PTSF and vehicle count. Generally, PTSF values tend to decrease as the analysis period increases, with a few exceptions, particularly during shorter time intervals. Furthermore, PTSF values appear to become more stable at longer time intervals, such as peak hour or 2 hour. On the other hand, PTSF values for southbound traffic on Jackrabbit Lane and northbound traffic on Highway 287 are inconsistent with trends from the rest of the data. Specifically, PTSF values for southbound traffic on Jackrabbit Lane increase as peak time interval increases, which is contradictory to the characteristics of peak traffic and its correlation to PTSF.

Logically, PTSF values should decrease as peak time period increases because lower volumes should result in a lower likelihood of interactions between vehicles on the roadway (note: volume expressed in vehicles per hour is the highest during the peak 15 minute period and declines as time increases). Also, PTSF values for northbound traffic on Highway 287 are significantly large considering the low traffic volume this highway experiences.

Examination of Traffic Level and Heavy Vehicle Percentage

As with the weighted-average approach, the purpose of this section is to investigate two variables, traffic peaking characteristics and percentage of heavy vehicles that potentially have an effect on platooning and consequently on the PTSF values. For this purpose, the PTSF as a function of peak time period was plotted against the percentage of heavy vehicles and the traffic intensity ratio TIR, which was discussed in the previous chapter. Figure 17 displays these plots for all six data sets discussed in Chapter 5.

Referring to the charts in Figure 17, PTSF and the percentage of heavy vehicles are plotted on the left vertical axis on the graphs in Figure 17 while the TIR is plotted as a percentage on the right vertical axis. As with the previous analysis, a headway cut-off value of 6 seconds was used to establish the probability P_p for this analysis. From the figure, relationships between the dependent variable, PTSF, and the other variables percentage of heavy vehicles and TIR are clearly present. For example, the graph representing northbound traffic from the Highway 287/12 study site shows a steady decrease in both the percentage of heavy vehicles and the TIR overtime. Consequently, the PTSF values decrease in a similar fashion.

Furthermore, the data from Jackrabbit Lane shows a correlation between increasing percentage of heavy vehicles and PTSF results from the probabilistic method. Specifically, PTSF values from the probabilistic method have a direct relationship to the percentage of heavy vehicles as time increases. Referring to the graphs representing the Highway 287 study site where the percentage of heavy vehicles is nearly constant throughout time, PTSF values correlate to the trends for the TIR. Similar trends can be established for each study site in that PTSF values have a direct relationship to the percentage of heavy vehicles and traffic volume represented by the TIR. These patterns are consistent with results from the similar analysis completed for the weighted average approach in Chapter 8.

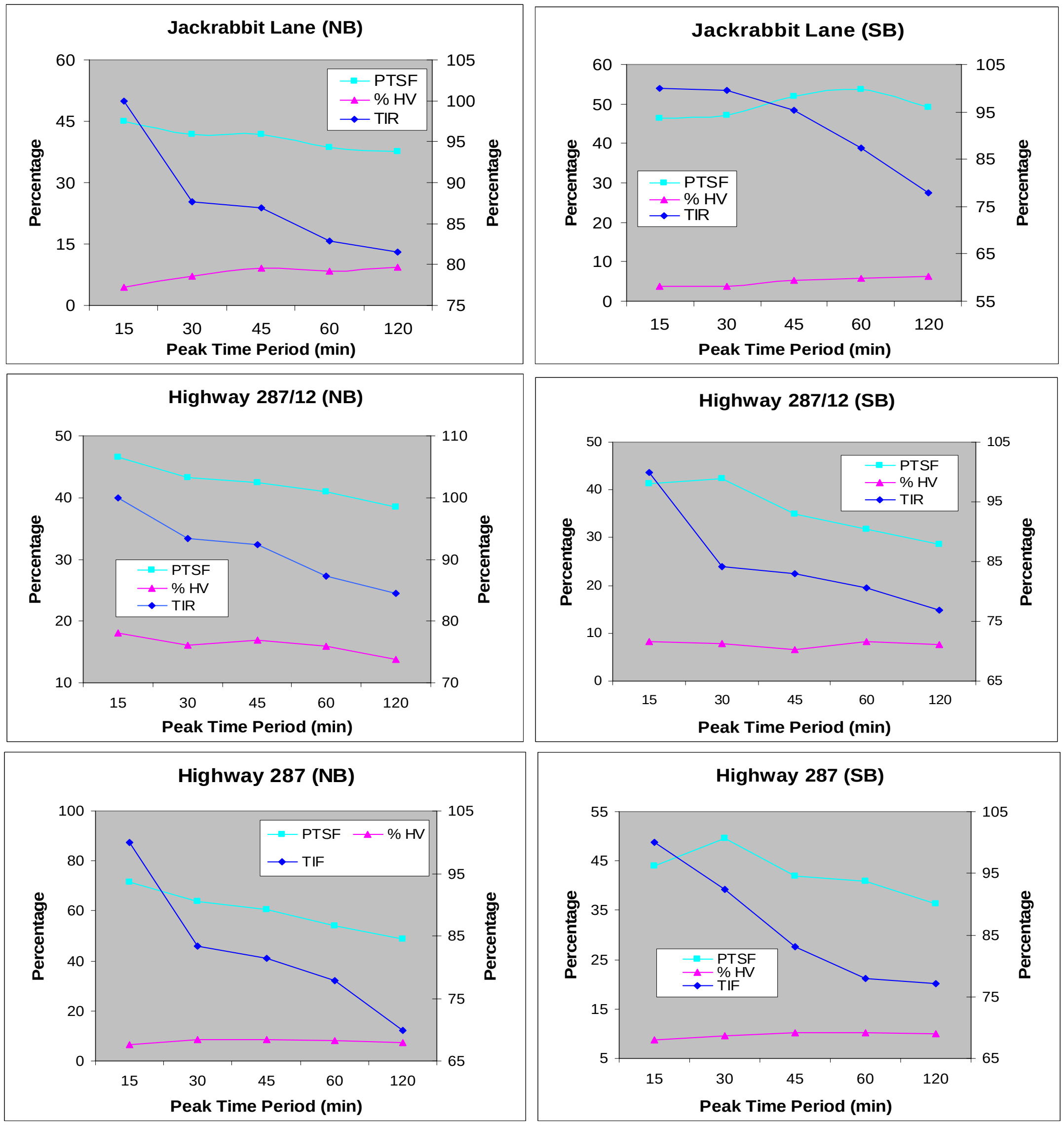

Figure 17 Heavy vehicle, TIF, and PTSF versus Time for Probabilistic Approach

As with the weighted average approach, a multiple linear regression analysis was completed in Microsoft Excel to investigate how percentage of heavy vehicles and the TIR effect PTSF results from the probabilistic approach. The prediction equations and R Squared values corresponding to each study site are shown in Table 13. Regression output summaries can be found in Appendix C.

According to the table, most of the variability in PTSF values can be attributed to the combined effect of the percentage of heavy vehicles and the TIR, while the rest is attributed to other factors not included in this analysis and to random occurrence. With the exception of southbound traffic on Highway 287/12 and Jackrabbit Lane, the R Squared values are relatively high as they varied in the range between 0.79 and 0.98. This means that there is a high correlation between TIR and the percentage of heavy vehicles and the PTSF as estimated using the probabilistic method for most study sites.

The lower R-squared value at Highway 287/12 - SB is mostly attributed to the presence of a passing lane around 2 miles upstream of that site, which has a large effect on platooning and thus the PTSF. Jackrabbit Lane has considerably high volumes and frequent driveways, which effect platooning and may be the reasons for the smaller R Squared value. Nonetheless, it would seem that the probabilistic approach yielded PTSF values that are logically sensitive to platooning variables such as the percentage of heavy vehicles, traffic level, and the presence of passing lanes. It should be noted that the results of the regression analysis are generally consistent with those from the weighted average approach discussed in Chapter 7.

Table 13 Multiple Regression for Probabilistic Approach

Study Site	Linear Regression Model	R Squared
Highway 287 (NB)	PTSF = -51.850 + -3.750 (%HV) + 0.993 (TIR)	0.9821
Highway 287 (SB)	PTSF = -197.2824 + 14.282 (%HV) + 1.169 (TIR)	0.7968
Highway 287/12 (NB)	PTSF = -0.206 + 0.438 (%HV) + 0.387 (TIR)	0.9818
Highway 287/12 (SB)	PTSF = -9.048+ 1.117 (%HV) + 0.426 (TIR)	0.5897
Jackrabbit Lane (NB)	PTSF = 3.496 + 0.149 (%HV) + 0.415 (TIR)	0.9160
Jackrabbit Lane (SB)	PTSF = -29.604 + 5.078 (%HV) + 0.582 (TIR)	0.5829

Effect of Platoon Size on PTSF

The objective of this analysis is to investigate the effect platoon size, represented by the number of vehicles traveling within the platoon, has on the PTSF using the probabilistic method. The literature does not suggest a specific number of vehicles required to form a vehicular platoon. However, platoon size is deemed as an important indicator to distinguish between faster vehicles traveling with short headways (not impeded by slow-moving vehicles) and platoons formed by slow-moving vehicles which tend to be growing in size.

Therefore, PTSF values were determined for platoon sizes of 2 vehicles or more, 3 vehicles or more, 4 vehicles or more, and 5 or more vehicles using the highest peak hour data from each data set. In other words, platoons were first classified as 2 or more consecutive vehicles traveling at or less than the pre-specified headway cut-off value. Next, platoons were classified as 3 or more consecutive vehicles traveling at or less than the pre-specified headway cut-off value, and so on, up to 5 consecutive vehicles. Consistent with previous analyses, a headway cut-off value of six seconds was used to complete this investigation. Accordingly, PTSF values from the probabilistic method were determined for this headway cut-off value and each of the platoon sizes given above. This analysis was completed for each of the six data sets using data from the peak hour time interval. The results from this analysis are displayed in Figure 18.

The results displayed in Figure 18 agree with the concepts of platooning and PTSF. Namely, it is expected that PTSF should be the highest when platoons are classified as any 2 or more consecutive vehicles that are traveling at less than a specified headway cut-off value. This is represented in Figure 18 where the PTSF values corresponding to platoons classified by 2 or more vehicles has the highest PTSF value and the PTSF consequently decreases as the number of vehicles used to classify platoons decreases.

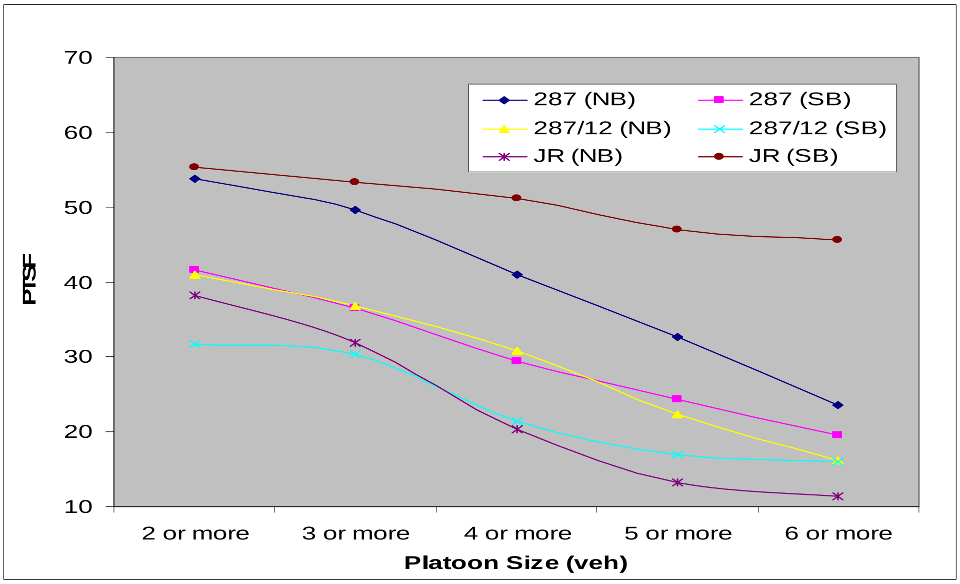

Figure 18 PTSF versus Platoon Size using Probabilistic Method

To further analyze the effect of platoon size using the probabilistic method, the two probabilities, P_p and P_t, which were used to establish the PTSF values in Figure 18, have been plotted against the various platoon sizes. The resulting graphs are displayed in Figure 19. Referring to Figure 19, two trends are established within the data. First, the proportion P_p decreases as the number of vehicles considered to represent a vehicular platoon increases. This is intuitive as P_p represents the proportion of vehicles within the traffic stream that are traveling within platoons. As the number of vehicles representing a vehicular platoon increases from 2 or more to 3 or more, to 4 or more, etc., the number of vehicles considered to be traveling in platoons should logically decrease. Therefore, the proportion of the entire traffic stream that is traveling within platoons will consequently decrease.

On the contrary, the proportion P_t tends to increase as a function of platoon size. This trend means that the size of the platoon is directly related to the number of vehicles within the platoon that are traveling involuntarily at the platoon speed. These results are consistent with those from Chapter 6 in that larger platoons are normally associated with slower speeds and more vehicles impeded by the platoon leaders.

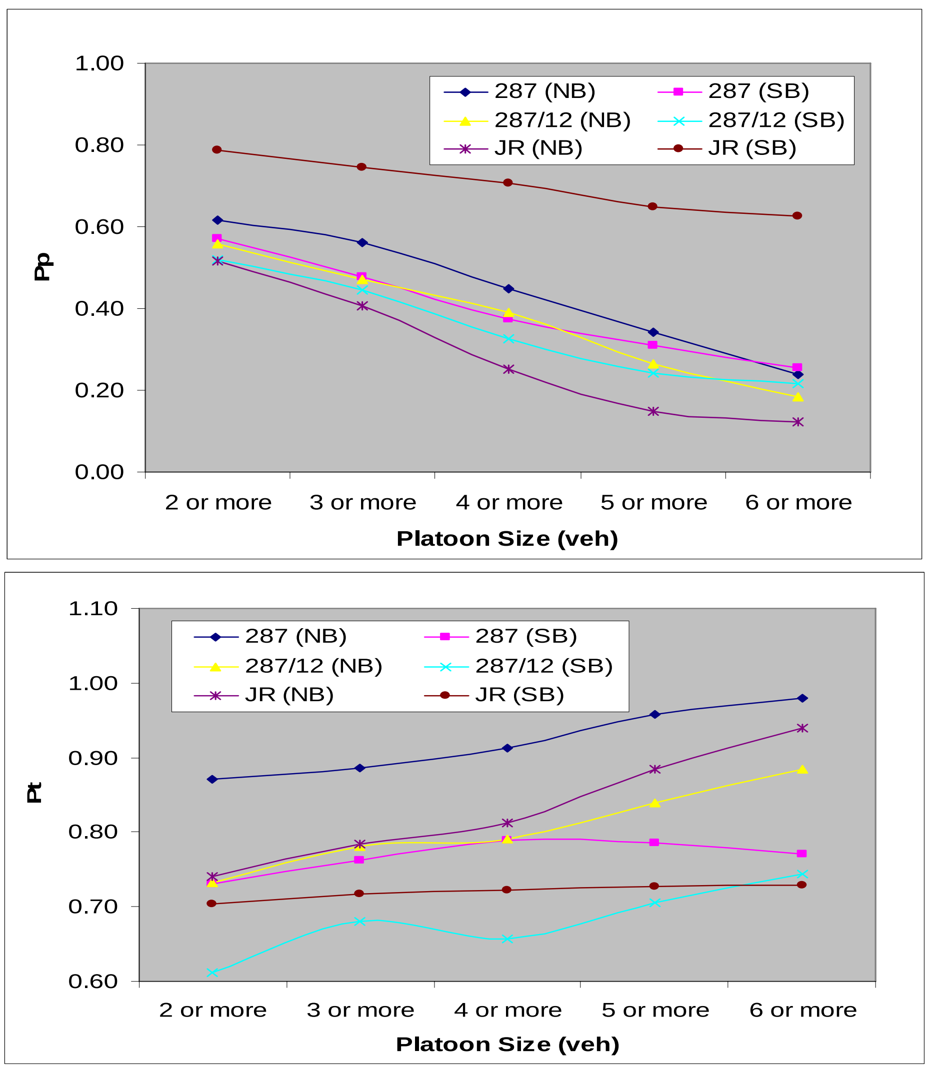

Figure 19 P_p and P_t versus Platoon Size using Probabilistic Method

Chapter Summary

The analyses provided in this chapter aimed at validating the probabilistic approach using field data. A few conclusions can be drawn from those analyses. First, the probabilistic approach provided PTSF values that realistically corresponded to the main variables of interest. Specifically, the PTSF values were reasonably sensitive to the traffic volume at various study sites.

The regression analysis showed that the PTSF values from the probabilistic method appear to be responsive to traffic peaking characteristics represented by the TIR. Furthermore, the regression analysis showed PTSF values to be sensitive to the percentage of heavy vehicles within the traffic stream. As these two variables greatly influence platooning, it is important that any reliable method capture their effect.

Finally, results from the platoon size analysis demonstrated two important concepts within the probabilistic approach. First, the probability of a vehicle being part of a vehicular platoon, P_p, is inversely proportional to the number of vehicles used to establish a vehicle platoon. This finding is intuitive Secondly, the probability of a vehicle traveling involuntarily in a platoon at a speed lower than their desired speed, P_t, tends to be directly proportional to the number of vehicles in the platoon.

CHAPTER 9

PTSF ESTIMATION USING THE HCM 2000 AND PROPOSED METHODS

The purpose of this chapter is to compare the PTSF as estimated by the two proposed methods with PTSF values from the HCM procedures. Specifically, the analysis compares results from the weighted average and the probabilistic approaches with results from the HCM using the software package HCS 2000 and the 3-second headway surrogate field measure. As the analyses of the weighted average and the probabilistic methods are applicable to directional travel, the directional analysis of the HCM procedures was used.

PTSF Estimation Using HCM 2000 Procedures

The HCM 2000 provides theoretical equations aimed at estimating PTSF based on various characteristics of two-lane highways. Furthermore, the HCM 2000 provides a surrogate field measure intended to estimate PTSF. The following sections investigate these procedures using the data from the six study sites discussed in Chapter 5.

PTSF Using Theoretical Equations

The theoretical equations outlined in the HCM 2000 were applied to estimate PTSF using the Highway Capacity Software 2000. The Highway Capacity Software 2000 is the computer software accompanying the HCM 2000 which incorporates all the analytical procedures outlined in the HCM 2000.

To complete this analysis, HCS 2000 requires various inputs relative to each of the study sites being investigated. These inputs are lane width, shoulder width, highway segment length, volume in analysis direction and opposing direction, peak hour factor, percent trucks, buses, and RVs, percent no passing zone, and the number of access points. Also, since the Highway 287/12 study site was located near a passing zone, the length of the passing lane and the distance of the study site from the passing lane were needed to complete the analysis on this study site. Table 14 displays the values input into HCS 2000 for each of the study sites. Table 15 displays the PTSF results from the HCS 2000 analysis.

Table 14 Highway Characteristics Required for HCS 2000 Software

Study Site	Lane Width (ft)	Shoulder Width (ft)	Length (miles)	Vol. (vph)	Vol. Opp. (vph)	PHF	Trucks & Buses (%)	RVs (%)	No-Passing (%)	Number of Access Points
287 (NB)	12	3	1.96	196	284	0.778	1	1	33	2.55
287 (SB)	12	3	1.96	284	196	0.780	1	1	50	1.53
287/12 (NB)	12	4	3.84	290	316	0.873	2	1	23	1.56
287/12 (SB)	12	4	3.84	316	290	0.806	1	2	23	2.08
JR (NB)	12	4	2.00	295	755	0.829	3	1	5	3.00
JR (SB)	12	4	2.00	755	295	0.874	14	4	5	3.00

Table 15 PTSF Results from HCS 2000

Study Site	Vol. (vph)	Vol. Opp. (vph)	PTSF (%)	ATS (mph)	LOS
Highway 287 (NB)	196	284	68.4	59.3	D
Highway 287 (SB)	284	196	82.2	58.9	E
Highway 287/12 (NB)	290	316	72.2	57.7	D
Highway 287/12 (SB)	316	290	59.9	62.8	C
Jackrabbit Lane (NB)	295	755	81.3	56.8	E
Jackrabbit Lane (SB)	755	295	90.3	52.7	E

According to the HCS results, only Highway 287/12 in the southbound direction is operating at a LOS better than D. This is expected, as the study site has a passing lane about 2.0 miles upstream from the observation point, which should lower the PTSF significantly. Nonetheless, all the PTSF values are greater than 50%, which are significantly high considering the traffic volumes.

PTSF Using 3-Second Surrogate Measure

As mentioned in Chapter 2, the HCM 2000 suggests a surrogate field measure of 3-second headways be used to establish the proportion of vehicles traveling in platoons, and hence the PTSF. Therefore, the PTSF based on this surrogate measure has been established for each of the study sites. As the HCM uses the peak hour for analysis and design purposes, this was the time period used for this analysis. The results from this analysis are shown in Table 16. Results from the 3-second headway surrogate measure are significantly lower than the results from the HCM equations. However, the PTSF values still seem somewhat high, specifically at the highway 287 and highway 287/12 study sites where traffic volume is below one-third of the highway's capacity.

Table 16 PTSF Values Based on 3-Second Headway Surrogate Measure

Study Site	Total Vehicles	Vehicles Traveling at or less than 3 seconds headways	PTSF
Highway 287 (NB)	290	114	39.3
Highway 287 (SB)	316	103	32.6
Highway 287/12 (NB)	196	81	41.3
Highway 287/12 (SB)	284	115	40.5
Jackrabbit Lane (NB)	295	101	34.2
Jackrabbit Lane (SB)	755	395	52.3

Comparison of PTSF Estimation by Various Methods

The purpose of this analysis is to evaluate the new concepts against the HCM 2000 procedures discussed in the previous section. In this regard, Table 17 displays PTSF values for the six study sites used in this research. The PTSF values represent the highest peak hour traffic volume for each of the study sites. Furthermore, the values for the probabilistic method were found using a headway cut-off value of six seconds to establish vehicle platoons.

Referring to Table 17, it appears that both new methods provide PTSF values that are significantly lower than the HCM 2000 equation. In this regard, the HCM 2000 equations provide extremely high PTSF values considering the traffic levels experienced at the study site locations. This overestimation by the HCM 2000 equations can be seen clearly from the PTSF values (i.e. 81.3 and 90.3) for Jackrabbit Lane, where the traffic volume during the highest peak hour was around fifty percent of the capacity of the highway. As the PTSF values shown in the table are for various locations, it is difficult to discern patterns across the methods. Therefore, the following analysis was completed to deal with this issue.

Table 17 Comparison of HCM 2000 and New Proposed Methods

Study Site	HCM 2000 Equations	HCM 2000 Surrogate Measure	Probabilistic	Weighted Average
287 (NB)	68.4	39.31	40.94	68.73
287 (SB)	82.2	32.59	31.75	35.73
287/12 (NB)	72.2	41.33	53.79	42.66
287/12 (SB)	59.9	40.49	41.69	21.04
JR (NB)	81.3	34.24	38.15	33.48
JR (SB)	90.3	52.32	55.35	44.47

As different highways possess distinctive characteristics in regard to lane and shoulder width, percent no-passing zones, traffic volume, etc., a more complete comparison between the methods was completed at individual study sites. Therefore, PTSF values were established based on hourly volumes from various times throughout the day for each of the study sites. The results from this analysis can be seen in Table 18. It should be noted that all variables used for the HCM 2000 equations, except for those listed in Table 18, were the same as those listed previously in Table 14.

Table 18 PTSF Based on Various Hourly Volumes for All Data Sets

	Data Characteristics			PTSF			
Study Site	**Volume (vph)**	**Opposing Volume (vph)**	**% heavy vehicles**	**HCM Equations**	**HCM Surrogate Measure**	**Probabilistic**	**Weighted Average**
Jackrabbit Lane Southbound	755	295	5.7	90.3	52.3	55.3	44.5
	501	280	11.2	84.00	41.2	40.4	41.4
	390	338	9.2	75.6	41.0	38.9	50.0
	298	68	3.4	63.6	32.6	28.7	19.0
	192	198	7.3	62.8	18.8	19.3	25.8
Jackrabbit Lane Northbound	295	755	8.5	81.3	34.2	38.2	37.6
	244	546	7.4	70.5	30.7	26.8	34.0
	198	301	4.5	65.3	24.2	22.2	28.7
Highway 287 Southbound	284	196	10.2	82.2	32.6	31.8	35.7
	244	246	12.3	78.4	33.2	37.6	37.2
	173	160	15.7	72.9	27.9	32.1	30.1
Highway 287 Northbound	296	128	12.9	72.9	36.6	48.8	38.9
	263	139	12.9	76.4	36.1	47.0	90.3
	196	284	8.2	68.4	39.3	40.9	68.7
Highway 287/12 Southbound	316	290	8.2	59.9	40.5	41.7	21.0
	249	254	3.6	57.8	31.7	31.3	14.3
	173	233	4.3	52.9	23.4	21.7	-1.2
Highway 287/12 Northbound	290	316	15.9	72.2	41.3	53.8	42.7
	252	288	10.3	71.2	34.1	30.8	15.9
	195	177	13.8	66.5	27.7	33.0	28.0

Referring to Table 18, a few conclusions can be drawn about the validity of the new methods. First, the probabilistic approach provides PTSF values that generally decline as traffic volume declines. As a significant decrease in traffic volumes should correlate to a decline in vehicle platooning and therefore a decrease in PTSF, the probabilistic method seems to effectively capture this aspect.

Less consistency can be found within PTSF values from the weighted average approach. As can be seen from the table, the weighted average approach seems to provide reliable results for higher traffic volumes, with inconsistencies arising at lower traffic volumes. From these trends, it appears that the probabilistic method provides more reliable results than the weighted average approach.

As with the previous analysis, the two HCM 2000 methods provide considerably different results when compared against one another. The tendency for the two methods to be different is consistent with results from Luttinen (2001) and Dixon et al (2002). Also, the HCM 2000 equations provide PTSF values that are significantly high considering the traffic volumes being investigated.

PTSF results from the probabilistic approach are relatively close to those from the HCM 3-second surrogate measure. The fact that the PTSF values from the probabilistic approach are drastically less than the HCM 2000 equation and slightly less than the HCM 2000 3-second surrogate measure appears to show the potential that the new method has in addressing the limitations of the current HCM procedures.

Besides traffic volume, other factors such as percent no-passing zones, truck traffic, and road geometric features play a role in platooning and PTSF. To investigate the ability of the new methods to model the factors listed previously, a multiple linear regression was completed on the data. In particular, the regression model was completed using PTSF as the dependent variable and the following factors as independent variables:

- Traffic Volume in vehicles per hour (vph)
- Opposing Traffic Volume in vehicles per hour (vph)
- Percent Heavy Vehicles
- Percent No-Passing Zones

The multiple linear regression analysis was completed for the PTSF data from Table 18, with the exception of southbound traffic on Highway 287/12 due to the influence of the passing lane upstream of the study site. As passing lanes considerably affect PTSF and only one of the six data sets contained this influence, it was not considered by this analysis. Regression results are provided in Table 19 (see Appendix C for regression output summaries).

Table 19 Multiple Linear Regression Results for Probabilistic Method

Method	**Linear Regression Model**	**R Squared Value**
Probabilistic Approach	PTSF = 0.05784 (volume in vph) + 0.00799 (opposing volume in vph) + 1.48486 (% heavy vehicles) + 0.11363 (% no-passing zones)	0.9758
Weighted Average Approach	PTSF = 0.04716 (volume in vph) + 0.002104 (opposing volume in vph) + 1.22248 (% heavy vehicles) + 0.31156 (% no-passing zones)	0.8805
HCM 2000 Surrogate Field Measure	PTSF =12.009 + 0.05112 (volume in vph) + 0.008908 (opposing volume in vph) + 0.13031 (% heavy vehicles) + 0.13732 (% no-passing zones)	0.7339

In this table, the equations show the relative influence each variable has on PTSF estimates using the two methods. In particular, it should be noted that all variable coefficients are positive in sign. This means that each of these variables increases PTSF, which is consistent with the concept of PTSF as outlined by the HCM 2000.

Referring to the R Squared values in the table, the correlation between the various variables and PTSF is high for the new methods and slightly lower for the HCM 2000 surrogate measure. The higher correlation between the variables shows that the new methods are more effective in capturing the effect of these variables, which are important in estimating PTSF. The high R Squared values combined with the reasonableness of the regression model shows that the new methods are successful in estimating PTSF on two-lane, two-way highways. However, the HCM 2000 surrogate field measurement appears to be considerably less successful in this regard. These results are expected as the HCM 2000 surrogate measure is based solely on computer simulation, while the new methods are based on sound traffic theory.

Of the methods, the probabilistic method appears to be an extremely promising model. In particular, the variation in PTSF values under the probabilistic approach is almost completely explained by these variables (97.6%).

Chapter Summary

This chapter provided a comparison of the PTSF values estimated using the new methods with their counterparts from the HCM 2000 procedures. As mentioned in Chapters 2 and 3, the two-lane highway analysis procedure outlined in the HCM 2000 has inherent limitations that cause gross overestimates of the performance measure PTSF.

One of the reasons for this overestimation may stem from the inability of these procedures to distinguish between vehicles traveling voluntarily in platoons and those traveling involuntarily in platoons. Therefore, resolving this issue is one of the objectives of the new procedures. Consequently, the ability of the new methods to accurately quantify PTSF by considering only those vehicles that travel involuntarily in platoons at less than their desired speeds is in the core of the proposed methods.

The PTSF results using the HCM 2000 procedures provided in this chapter are consistent with the overestimation expressed earlier in Chapters 2 and 3. Specifically, the PTSF values provided by the HCM 2000 equations were considerably higher than those measured in the field using the 3-second headway rule. There is general consistency between the PTSF estimated using the new procedure and that measured in the field using the HCM 3-second headway rule. However, the results from either of the new methods should be more reliable as it is based on logical traffic theories and not an empirical rule of thumb.

Both new methods provided PTSF values that were significantly lower than those from the HCM 2000 equations. Apparently, the methods seem to effectively alleviate the overestimation experienced by the HCM 2000 equations. Also, comparing various traffic volumes by site revealed that the probabilistic is highly sensitive to fluctuations in volume, while the weighted average is less effective in this regard. Therefore, it seems safe to conclude that the probabilistic method is the more appropriate method for estimating PTSF on two-lane, two-way highways.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

As mentioned in the introduction of the thesis, the current research is aimed at examining two new concepts / methodologies in estimating the PTSF. Also, this research examined the HCM 2000 procedures for analyzing two-lane highways. Consistent with observations in the current literature, this study confirmed that the HCM 2000 procedures are inaccurate for determining performance on two-lane, two-way highways. In particular, the measure for estimating performance on those highways, the PTSF, was found to be significantly overestimated by the HCM 2000 when compared to their counterparts from field measurements. It is important to mention that the HCM 2000 procedures were developed relying solely on simulation results rather than empirical investigations.

Two new methods that are intended to address the limitations in the HCM 2000 procedures were evaluated. The first method, the weighted-average approach, is aimed at estimating PTSF by separating vehicles into performance categories and establishing their effect on the traffic stream. The second method, the probabilistic approach, estimates PTSF by establishing the probability of vehicles traveling involuntarily within a platoon at less than their desired travel speed.

In accordance with the scope of this study, these two approaches were tested using field data from three study sites in Montana. As part of this evaluation, the platooning phenomenon specific to two-lane, two-way highways was also investigated. The most important findings of the current research are:

1. Results revealed that as the number of vehicles within a platoon increases, the mean travel speed of the platoon decreases. This is consistent with the research hypothesis that the slower the travel speed of a particular vehicle, the more the impedance to traffic, and the higher the amount of platooning on two-lane highways.

2. It was shown that vehicle travel speeds have a direct relationship with time headway. Travel speed increases with the increase in time headway up to around a headway value of 6 seconds, beyond which the relationship flattens out as there is no noticeable gain in speed with the increase in time headway. This result suggests that, in general, successive vehicles in the traffic stream cease to interact in a car-following mode beyond a headway of 6 seconds.

3. While the concept of the weighted average approach is based on the speeds of heavy vehicles and passenger cars, it seems that this approach best works when vehicles are classified by their performance.

4. Both methods provided PTSF values that are consistent with the concepts of vehicle interaction on two-lane, two-way highways. In this regard, the methods were shown to accurately estimate the effect of traffic level, the percentage of heavy vehicles, and the effect of passing lanes. In fact, the PTSF values from the two new methods were shown to have correlations to

these variables of 0.70 or higher. As these are among the most important determining factors of vehicle platooning on two-lane, two-way highways, it is important for any reliable PTSF estimation method to be sensitive to these factors.

5. A comparison with the current HCM 2000 procedures revealed the new methods provide PTSF values that are lower than the values provided by the HCM 2000 procedures. This gave extra assurance that the new methods have the potential in eliminating much of the overestimation observed with the current HCM 2000 procedures.

6. There is general consistency between the PTSF estimated using the new procedure and that measured in the field using the HCM 3-second headway rule. However, the results from either of the new methods should be more reliable as it is based on logical traffic theories and not an empirical rule of thumb.

7. Out of the two new PTSF estimation methods, the probabilistic approach seems to be superior as it consistently performed better than the weighted average method throughout the analyses. Specifically, the PTSF estimated using the probabilistic approach proved to be highly sensitive to traffic volume and its temporal variations, percentage of heavy vehicles, and the influence of passing lanes.

Recommendations for Future Research

- Conduct further empirical studies using data from a wider range of highways. In this regard, the following investigations are recommended:
  - Test method using a larger range of volumes, especially high volumes.
  - Test method using data from Class II highways.
  - Incorporate other variables related to two-lane, two-way highway geometry (i.e. steep grades, climbing lines, traffic mix)
  - For convenience, it would be advantageous to complete data collection using traffic counters that specifically provide vehicle headways. This would accelerate both the data processing and the any analyses completed using the data.

- The probabilistic method currently lacks the ability to account for the fact that some drivers may tolerate a small difference in speed when they follow slower vehicles. Improving speed by such a small magnitude may not be enough incentive for those vehicles to perform passing maneuvers. To address this limitation, a modification to the method would be to consider this traffic phenomenon in determining the probability P_t.

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APPENDICES

APPENDIX A:

HCM 2000 TWO-LANE HIGHWAY ANALYSIS PROCEDURES

Two-Way Segments

Average Travel Speed

As described in the HCM 2000, average travel speed is estimated using free flow speed (FFS), the demand flow rate, and an adjustment factor for the percentage of no-passing zones. For two-way segments, ATS is estimated using the following equation (TRB 2000):

$$ATS = FFS - 0.0125 v_p - f_{np}$$

where

v_p = passenger-car equivalent flow rate for peak 15-min period (pc/h)

f_{np} = adjustment for percentage of no-passing zones on percent time- spent-following

Percent Time Spent Following

As described in the HCM 2000, percent time-spent-following is estimated from the demand flow rate, directional distribution of traffic, and the percentage of no-passing zones. For two-way segments, PTSF can be determined using the equation below (TRB 2000):

$$PTSF = BPTSF + f_{d/np}$$

where

PTSF = percent time-spent-following for both directions of travel combined

BPTSF = base percent time-spent-following for both directions of travel combined

$f_{d/np}$ = adjustment for the combined effect of the directional distribution of the traffic and of the percentage of no-passing zones on percent time- spent-following

BPTSF is determined by the following equation (TRB 2000):

$$BPTSF = 100 \left(1 - e^{-0.000879 \, v_p}\right)$$

where

v_p = demand flow rate

Directional Segments – No Passing Lane

Percent Time Spent Following

Again, from the HCM 2000, percent time-spent-following is estimated from the demand flow rate, directional distribution of traffic, and the percentage of no-passing zones. For directional segments, PTSF is determined using Equation 20-16 (HCM 2000):

$$PTSF_d = BPTSF_d + f_{np}$$

where

$PTSF_d$ = percent time-spent-following in the direction analyzed

$BPTSF_d$ = base percent time-spent-following for both directions of travel combined

f_{np} = adjustment for percentage of no-passing zones on percent time- spent-following

$BPTSF_d$ is given by equation 20-17 (HCM 2000):

$$BPTSF_d = 100\left(1 - e^{av_d{}^b}\right)$$

where

v_d = passenger-car equivalent flow rate for the peak 15-min period in the analysis direction (pc/h)

a,b = Coefficient whose values are determined from the flow rate in the opposing direction of travel.

Directional Segments – Passing Lane

Percent Time Spent Following

According to the 2000 HCM, Percent time-spent-following for segments with passing lanes varies as a function of distance from the passing lane. Therefore an average percent time-spent-following with the passing lane in place can be determined using Equation 20-19 (HCM 2000):

$$PTSF_{pl} = \frac{PTSF_d\left[L_u + L_d + f_{pl}L_{pl} + \left(\frac{1+f_{pl}}{2}\right)L_{de}\right]}{L_t}$$

where

$PTSF_{pl}$ = percent time-spent-following for the entire segment including passing lane

$PTSF_d$ = percent time-spent-following for entire segment without the passing lane as described in the previous section

f_{pl} = factor for the effect of a passing lane on percent time-spent-following (see Exhibit 20-24)

L_d = length of two-lane highway downstream of the passing lane and beyond its effective length (km)

L_t = total length of analysis segment (km)

L_u = length of two-lane highway upstream of the passing lane (km)

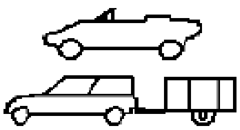
L_{pl} = length of passing lane including tapers (km)

L_{de} = downstream length of two-lane highway within the effective length of the passing lane (km)

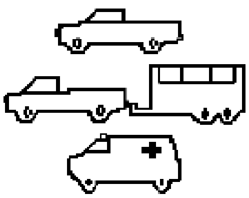
APPENDIX B:

AASHTO VEHICLE CLASSIFICATION SCHEME

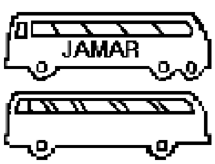
Class 1 - Motorcycles. This class includes all two- or three-wheeled motorized vehicles. These vehicles typically have a saddle-type of seat and are steered by handlebars rather than a steering wheel. This includes motorcycles, motor scooters, mopeds, motor-powered bicycles and three-wheel motorcycles.



Class 2 - Passenger cars. This class includes all sedans, coupes and station wagons manufactured primarily for the purpose of carrying passengers, including those pulling recreational or other light trailers.

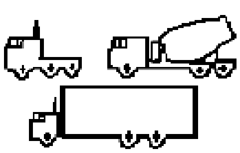


Class 3 - Pickups, Vans and other 2-axle, 4-tire Single Unit Vehicles. This class includes all two-axle, four tire vehicles other than passenger cars, which includes pickups, vans, campers, small motor homes, ambulances, minibuses and carryalls. These types of vehicles which are pulling recreational or other light trailers are included.

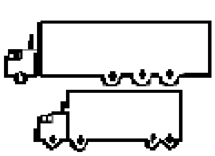


Class 4 - Buses. This class includes all vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This includes only traditional buses, including school and transit buses, functioning as passenger-carrying vehicles. All two-axle, four tire minibuses should be classified as Class 3. Modified buses should be considered to be trucks and classified appropriately.

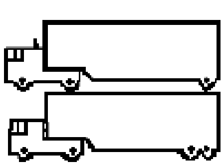
Class 5 - Two-Axle, Six-Tire Single Unit Trucks. This class includes all vehicles on a single frame which have two axles and dual rear tires. This includes trucks, camping and recreation vehicles, motor homes, etc.



Class 6 - Three-Axle Single Unit Trucks. This class includes all vehicles on a single frame which have three axles. This includes trucks, camping and recreation vehicles, motor homes, etc.

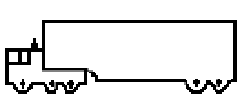


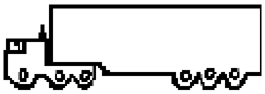
Class 7 - Four or More Axle Single Unit Trucks. This class includes all vehicles on a single frame with four or more axles.



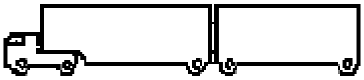
Class 8 - Four or Less Axle Single Trailer Trucks. This class includes all vehicles with four or less axles consisting of two units, in which the pulling unit is a tractor or single unit truck.

Class 9 - Five-Axle Single Trailer Trucks. This class includes all five-axle vehicles consisting of two units in which the pulling unit is a tractor or single unit truck.

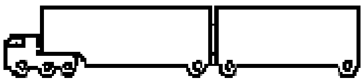




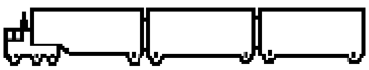
Class 10 - <u>Six or More Axle Single Trailer Trucks</u>. This class includes all vehicles with six or more axles consisting of two units in which the pulling unit is a tractor or single unit truck.



Class 11 - <u>Five or Less Axle Multi-Trailer Trucks</u>. This class includes all vehicles with five or less axles consisting of three or more units in which the pulling unit is a tractor or single unit truck.



Class 12 - <u>Six-Axle Multi-Trailer Trucks</u>. This class includes all six-axle vehicles consisting of three or more units in which the pulling unit is a tractor or single unit truck.



Class 13 - <u>Seven or More Axle Multi-Trailer Trucks</u>. This class includes all vehicles with seven or more axles consisting of three or more units in which the pulling unit is a tractor or single unit truck.

APPENDIX C:

MULTIPLE REGRESSION ANALYSIS

HIGHWAY 287: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.901645
R Square	0.812964
Adjusted R Square	0.781791
Standard Error	0.379452
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.755014	3.755014	26.07935	0.002207
Residual	6	0.863905	0.143984		
Total	7	4.618919			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	67.06921	0.295667	226.8404	4.95E-13	66.34574	67.79268
headway	0.299007	0.058551	5.106794	0.002207	0.155738	0.442275

HIGHWAY 287: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.847955
R Square	0.719027
Adjusted R Square	0.672198
Standard Error	0.22217
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.757884	0.757884	15.35438	0.007816
Residual	6	0.296157	0.049359		
Total	7	1.054041			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	70.29878	0.173113	406.0851	1.51E-14	69.87518	70.72237
headway	0.134331	0.034282	3.918466	0.007816	0.050447	0.218215

HIGHWAY 287/12: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.835938
R Square	0.698792
Adjusted R Square	0.648591
Standard Error	0.326752
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.486172	1.486172	13.91981	0.009726
Residual	6	0.6406	0.106767		
Total	7	2.126772			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	73.46338	0.254603	288.541	1.17E-13	72.84039	74.08637
headway	0.188109	0.050419	3.730926	0.009726	0.064739	0.31148

HIGHWAY 287/12: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.243938
R Square	0.059506
Adjusted R Square	-0.09724
Standard Error	0.124449
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.005879	0.005879	0.379625	0.560437
Residual	6	0.092925	0.015487		
Total	7	0.098804			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	64.21006	0.09697	662.1675	8.01E-16	63.97279	64.44734
headway	0.011832	0.019203	0.616137	0.560437	-0.03516	0.058819

JACKRABBIT LANE: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.820171
R Square	0.67268
Adjusted R Square	0.618127
Standard Error	0.292121
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.052235	1.052235	12.33068	0.012648
Residual	6	0.512008	0.085335		
Total	7	1.564243			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	63.1393	0.227619	277.3905	1.48E-13	62.58234	63.69627
headway	0.158282	0.045075	3.511507	0.012648	0.047987	0.268577

JACKRABBIT LANE: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.805952
R Square	0.649558
Adjusted R Square	0.591151
Standard Error	0.394237
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.72849	1.72849	11.12124	0.015712
Residual	6	0.932535	0.155422		
Total	7	2.661025			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	58.61587	0.307187	190.8152	1.4E-12	57.86421	59.36753
headway	0.202866	0.060832	3.334852	0.015712	0.054015	0.351716

HIGHWAY 287: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.982014
R Square	0.964351
Adjusted R Square	0.940585
Standard Error	9.244595
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	6935.64	3467.82	40.57708	0.006731
Residual	3	256.3876	85.46254		
Total	5	7192.028			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-130.23	72.42039	-1.79825	0.169978	-360.704	100.2441
% HV	-5.04833	5.898293	-0.8559	0.454973	-23.8193	13.72267
TIR	3.086902	0.442076	6.982736	0.006029	1.680018	4.493787

HIGHWAY 287: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.860859
R Square	0.741078
Adjusted R Square	0.568464
Standard Error	2.656659
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	60.6022	30.3011	4.293255	0.131751
Residual	3	21.17352	7.057839		
Total	5	81.77572			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-34.3909	92.65353	-0.37118	0.735169	-329.256	260.474
% HV	2.476691	6.405327	0.386661	0.724802	-17.9079	22.8613
TIR	0.472257	0.366089	1.290005	0.287491	-0.6928	1.637315

HIGHWAY 287/12: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.919345
R Square	0.845196
Adjusted R Square	0.741993
Standard Error	3.274654
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	175.641	87.82049	8.189643	0.060908
Residual	3	32.17008	10.72336		
Total	5	207.8111			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-30.9873	29.6807	-1.04402	0.373197	-125.445	63.46991
% HV	1.807153	1.771968	1.019856	0.382873	-3.83204	7.446346
TIR	0.443369	0.575919	0.769846	0.497455	-1.38946	2.276201

HIGHWAY 287/12: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.583386
R Square	0.340339
Adjusted R Square	-0.09943
Standard Error	12.6046
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	245.9071	122.9535	0.773896	0.535773
Residual	3	476.6279	158.876		
Total	5	722.5349			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-50.5339	63.08846	-0.801	0.481699	-251.31	150.2417
% HV	1.487211	8.490717	0.175157	0.872111	-25.534	28.50846
TIR	0.71976	0.728525	0.987969	0.396007	-1.59873	3.038252

JACKRABBIT LANE: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.889397
R Square	0.791027
Adjusted R Square	0.651712
Standard Error	10.58571
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1272.514	636.257	5.677963	0.095529
Residual	3	336.1718	112.0573		
Total	5	1608.686			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-61.0623	209.3526	-0.29167	0.789543	-727.316	605.1913
% HV	-2.23554	6.163168	-0.36273	0.740859	-21.8495	17.37841
TIR	1.534481	1.863533	0.823426	0.470622	-4.39611	7.465074

JACKRABBIT LANE: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.812414
R Square	0.660017
Adjusted R Square	0.433362
Standard Error	13.70304
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1093.586	546.793	2.911985	0.198238
Residual	3	563.3199	187.7733		
Total	5	1656.906			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	19.5465	220.332	0.088714	0.9349	-681.648	720.7412
% HV	7.465678	13.39951	0.55716	0.616287	-35.1776	50.10891
TIR	-0.27694	1.696752	-0.16322	0.880721	-5.67677	5.122881

HIGHWAY 287: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.991025
R Square	0.982131
Adjusted R Square	0.964261
Standard Error	1.653455
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	300.5187	150.2593	54.96129	0.017869
Residual	2	5.467824	2.733912		
Total	4	305.9865			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-51.85	20.66608	-2.50894	0.12886	-140.769	37.06894
% HV	3.749453	1.491197	2.514392	0.128405	-2.66665	10.16555
TIR	0.992859	0.120942	8.209402	0.014516	0.472489	1.513229

HIGHWAY 287: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.892635
R Square	0.796798
Adjusted R Square	0.593595
Standard Error	3.070121
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	73.91974	36.95987	3.921204	0.203202
Residual	2	18.85128	9.425642		
Total	4	92.77102			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-197.282	141.5265	-1.39396	0.298011	-806.222	411.657
% HV	14.28183	9.543387	1.496516	0.27319	-26.7801	55.34371
TIR	1.169344	0.573791	2.037925	0.178439	-1.29948	3.638169

HIGHWAY 287/12: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990854
R Square	0.981791
Adjusted R Square	0.963583
Standard Error	0.568064
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	34.79887	17.39943	53.91879	0.018209
Residual	2	0.645394	0.322697		
Total	4	35.44426			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.20632	5.544215	-0.03721	0.973696	-24.0611	23.64852
% HV	0.437963	0.308854	1.418026	0.291942	-0.89093	1.766855
TIR	0.387116	0.101211	3.82483	0.06206	-0.04836	0.822594

HIGHWAY 287/12: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.767887
R Square	0.58965
Adjusted R Square	0.1793
Standard Error	5.409132
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	84.0862	42.0431	1.436943	0.41035
Residual	2	58.51743	29.25871		
Total	4	142.6036			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-9.04773	27.59845	-0.32783	0.774174	-127.794	109.6988
% HV	1.170065	3.834225	0.305163	0.789072	-15.3273	17.6674
TIR	0.426337	0.350498	1.216375	0.347914	-1.08173	1.934408

JACKRABBIT LANE: NORTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.957091
R Square	0.916023
Adjusted R Square	0.832046
Standard Error	1.228365
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	32.91772	16.45886	10.90799	0.083977
Residual	2	3.017761	1.508881		
Total	4	35.93548			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.496202	25.4968	0.137123	0.903492	-106.208	113.2001
% HV	0.148869	0.732262	0.2033	0.857708	-3.0018	3.299538
TIR	0.415125	0.227849	1.821929	0.210051	-0.56523	1.395479

JACKRABBIT LANE: SOUTHBOUND

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.763479
R Square	0.5829
Adjusted R Square	0.1658
Standard Error	2.899391
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	23.49621	11.7481	1.397508	0.4171
Residual	2	16.81293	8.406467		
Total	4	40.30914			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-29.6037	57.38922	-0.51584	0.657329	-276.53	217.3222
% HV	5.078422	3.314848	1.532023	0.265206	-9.18422	19.34106
TIR	0.581767	0.446686	1.302406	0.322569	-1.34017	2.503702

WEIGHTED AVERAGE METHOD

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.920683
R Square	0.847657
Adjusted R Square	0.735578
Standard Error	19.19289
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	26645.47	6661.367	18.08351	5.1E-05
Residual	13	4788.771	368.367		
Total	17	31434.24			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
Volume (vph)	0.047157	0.028526	1.653116	0.12224	-0.01447	0.108783
Opposing Volume (vph)	0.021043	0.028004	0.751398	0.465799	-0.03946	0.081543
% heavy vehicles	1.222478	1.493075	0.818766	0.427675	-2.00311	4.44807
% no-passing zones	0.311557	0.391882	0.795027	0.440872	-0.53505	1.158166

PROBABILISTIC METHOD

SUMMARY
OUTPUT

Regression Statistics	
Multiple R	0.987807
R Square	0.975762
Adjusted R Square	0.893246
Standard Error	6.788472
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	24117.97	6029.494	130.8388	8.71E-10
Residual	13	599.0837	46.08336		
Total	17	24717.06			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
Volume (vph)	0.057843	0.01009	5.732981	6.9E-05	0.036046	0.07964
Opposing Volume (vph)	0.007997	0.009905	0.807396	0.433963	-0.0134	0.029396
% heavy vehicles	1.484862	0.528096	2.811724	0.014696	0.343979	2.625745
% no-passing zones	0.113633	0.138608	0.81982	0.427095	-0.18581	0.413077

HCM 2000 SURROGATE FIELD MEASUREMENT

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.856703
R Square	0.73394
Adjusted R Square	0.645254
Standard Error	4.74796
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	746.2381	186.5595	8.275671	0.001917
Residual	12	270.5175	22.54313		
Total	16	1016.756			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	12.00897	5.531903	2.170857	0.050717	-0.04401	24.06195
Volume (vph)	0.051127	0.009021	5.667437	0.000104	0.031471	0.070782
Opposing Volume (vph)	0.008908	0.00802	1.110683	0.288465	-0.00857	0.026382
% heavy vehicles	0.130306	0.421304	0.309292	0.762404	-0.78764	1.048248
% no-passing zones	0.137319	0.099562	1.379223	0.192989	-0.07961	0.354246