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Investigating the Effect of Freeway Congestion Thresholds on Decision-Making Inputs

Final Report

Tongbin Qu

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16. Abstract

Congestion threshold is embedded in the congestion definition. Two basic approaches exist in current practice for setting the congestion threshold. One common approach uses the “free-flow” or unimpeded conditions as the congestion threshold. Another approach uses target or “acceptable” conditions. The limited research that has been conducted on the congestion threshold issue focuses on operational problems or policy debates, but relatively little investigation of the effect on decision-making for transportation investment and resource allocation.

This research investigated the differences inherent in the threshold choices using detailed freeway data from seven metropolitan areas. Congestion performance measures of delay per mile, Travel Time Index and Planning Time Index were evaluated. This research specifically examined: 1) the ranking values of congestion measure for different congestion thresholds under a variety of real-world travel time distributions, 2) the relationship between change of congestion threshold and change of performance measure, and 3) the appropriateness of using speed limit as a congestion threshold choice by evaluating the peak and off-peak average speed changes in relation to a speed limit change in Houston, Texas.

The rankings of congestion measures for freeway segments hold steady across the congestion thresholds ranging from 60 mph to 30 mph and across the congestion measures. From an investment point of view, the congestion threshold speed used is not a concern for funding allocation.

The relationship between the delay values for an alternative threshold and the 60 mph threshold has a quadratic form. As the alternative threshold decreases further away from 60 mph, the increment is larger. The more congested a section is, the less the threshold affects measured congestion. For very congested sections, most of the delay is associated with speeds below 30 mph.

The posted speed limit affects travel time distribution in the free flow driving condition but does not affect travel time distribution during congested driving conditions. However, if the speed limit or a percentage of speed limit is used to estimate the congestion, the amount of congestion may be underestimated because the free flow speed is higher than the speed limit.

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Investigating the Effect of Freeway Congestion Thresholds on Decision-Making Inputs

by

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Report UTCM 09-12-11

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The Texas A&M University System

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DISCLAIMER

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EXECUTIVE SUMMARY

This project investigated the effect of freeway congestion thresholds on decision-making inputs. Although the congestion problem has been studied for several decades in the United States, there has not been a consensus on when congestion technically begins. Policy discussions about the size of the congestion problem and the need for solutions are often side-tracked by this threshold issue. This research project investigated the differences inherent in the threshold choices using detailed freeway data. Specifically, congestion measure values were examined for different congestion thresholds under a variety of real-world travel time distributions. Ultimately, the research helps to answer questions such as:

- Do rankings of congestion measures for freeway segments hold steady across different congestion thresholds?
- Is congestion-threshold speed a concern for funding allocations?
- What is the relationship between delay and congestion threshold?

The research conducted in this project comprised the dissertation of the author for her Ph.D. in Urban and Regional Science from Texas A&M University in August 2010. Thus the dissertation in its entirety serves as the final technical report, and it follows herein intact.

INVESTIGATING THE EFFECT OF FREEWAY CONGESTION THRESHOLDS ON DECISION-MAKING INPUTS

A Dissertation

by

TONGBIN QU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2010

Major Subject: Urban and Regional Planning

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Approved by:

Co-Chairs of Committee,	Eric Dumbaugh
	Timothy J. Lomax
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August 2010

Major Subject: Urban and Regional Planning

ABSTRACT

Investigating the Effect of Freeway Congestion Thresholds on Decision-making Inputs.
(August 2010)

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Co-Chairs of Advisory Committee: Dr. Eric Dumbaugh
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DEDICATION

To everyone in my big family

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I would like to thank my committee co-chairs, Dr. Eric Dumbaugh and Dr. Tim Lomax, and my committee members, Dr. Michael Speed and Dr. Ming Zhang, for their guidance and support throughout the course of my Ph.D. study. Knowing them and learning from them is part of the great experience I had at Texas A&M University. I am especially thankful for the patience and encouragement of Dr. Tim Lomax. Without his guidance, advice and mentoring on every stage of this study, I would not be able to finish this dissertation.

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CHAPTER I
INTRODUCTION

Transportation has played a pivotal role in the support of economic development throughout human history. For the past few decades, a global growth phenomenon stimulated by globalization and trade liberalization has intensified the demand for the movement of goods. In addition, rapid urbanization further accelerates the demand for the transportation of both people and goods (*1*).

Although such vibrant growth may appear welcome, it has a darker side as well. Many negative impacts associated with transportation have been identified: 1) environmental damage; 2) energy consumption; 3) climate change, 4) traffic congestion, 5) transportation safety, and 6) social inequity (*1*). Perhaps among all the negative impacts, traffic congestion is the most noticeable and most frequently encountered.

In the United States, congestion levels continue to rise in cities of all sizes. The annual peak hour delay per traveler has almost tripled from 1982 to 2007 (*2*). In 2007 congestion cost travelers $87 billion, according to the most recent Urban Mobility Report (UMR) (*2*). This value is likely to grow because of the booming population and reliance on automobiles. It was estimated that from 1969 to 2001 the rate of increase in drivers was more than two times the rate of population growth and the rate of increase in household vehicles was more than four times the rate of population growth(*3*). The result of this phenomenon is that more than 87 percent of commuters drive to work in typical American metropolitan areas (*4*), and therefore, congestion seems to be ubiquitous in metropolitan areas.

In order to develop strategies to reduce congestion, extensive research has been conducted. At the national level, comprehensive congestion measures have been calculated for most large urban areas since the 1980s (*2*). More recently, Federal Highway Administration (FHWA) reports congestion for nearly 30 urban areas using

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This dissertation follows the style of *Transportation Research Record*.

real-time sensor data (*5*). Regionally, many transportation agencies have established explicit performance measures to monitor congestion as part of the transportation system performance (*6*-*8*).

Despite the effort, one fundamental issue remains about measuring congestion: "when does congestion start?", in other words, what is the congestion threshold. To date, there has not been a consensus on when congestion begins. Two basic approaches exist for setting this congestion threshold. 1) One common approach uses the free-flow or unimpeded conditions as the congestion threshold (*2*, *5*). With this approach of setting threshold, congestion measures all traffic delays beyond the free-flow or unimpeded conditions. 2) The other approach uses the target or "acceptable" conditions as the congestion threshold. The target or "acceptable" conditions are less ideal than the free-flow or unimpeded conditions. Additionally, within each approach there are more than one means of defining the free flow or the "acceptable" condition. Although both approaches have their advantages and can serve specific purposes, congestion measures using different approaches could yield very different results.

Nationwide, comparing congestion problems across areas can be challenging due to unique congestion thresholds used in different urban areas. The UMR uses free-flow condition (60 mph for freeways and 35 mph for arterials) as the threshold to rank the congestion problem for 90 urban areas. Questions that were asked regarding these thresholds are 1) whether a single threshold value for freeways and arterials is appropriate nationally and 2) whether the same ranking still holds when using different thresholds.

Furthermore, many transportation agencies use performance measures to help screen projects or set project priorities in the development of their transportation improvement program (TIP). Many agencies have also begun to use performance measures to help guide resource allocation decisions at the program level in the system planning and programming process (*9*). When investment decisions need to be made within the urban area itself, questions that were often asked are 1) whether all performance measures increase or decline in approximately the same ratio when moving from one congestion threshold to another and 2) whether there are situations where one threshold definition would alter the investment decisions.

Both nationally and regionally, policy discussions about the size of the congestion problem and the need for solutions are side-tracked by this threshold issue, providing opponents of transportation investment with a way to characterize supporters as “confused.” The limited research that has been conducted on this issue focuses on operational problems or policy debates. There is an increasing demand in knowing how much this issue matters in decision-making. The relationship between the change of congestion threshold and change of performance measure has not been investigated.

This research investigated the differences inherent in the threshold choices using detailed freeway data from metropolitan areas. In specific, the rankings of congestion measure values were examined for different congestion thresholds under a variety of real world travel time distributions. Freeway segments from different metropolitan areas were selected to represent the variety of traffic and land use patterns. In addition, the relationship between change of congestion threshold and change of performance measure was investigated under real world conditions. Furthermore, the research also investigated the appropriateness of using speed limit as a congestion threshold choice by examining the peak and off peak average speed changes in relation to a speed limit change in Houston, Texas.

The goal of this research was to provide evidence-based information for understanding congestion thresholds in general and the specific effects of freeway congestion thresholds on transportation investment decision-making inputs. This research was also intended to provide technical support to project or program-level investment decisions when using congestion measures to prioritize the improvement projects. The results of the study can be used by all levels of governmental agencies, including 1) municipalities responsible for prioritizing and selecting congestion reduction strategies, and 2) MPOs, State and Federal agencies overseeing urban transportation development.

Chapter II provides a review of previous research on all aspects of the congestion threshold issue. Chapter III introduces the research approach which includes a discussion of the research hypotheses and objectives, in addition to the proposed experimental design. Chapter IV provides information regarding the research procedures-focusing on study site selection and data aggregation processes. Chapter V presents the results of the experimental design and research findings. The final chapter offers conclusions based on the results and findings; describes the limitations of the research; and recommends the future research.

CHAPTER II
BACKGROUND

This chapter first provides an overview of congestion and its measurements related to the congestion threshold; then the chapter reviews the role of congestion measures as part of the overall performance measures in decision-making process, as well as the current practice and research of freeway congestion measures. Finally, this chapter reviews the data issues in estimating freeway congestion measures.

2.1 Overview of Congestion

2.1.1 Definition of Congestion

Although traffic congestion has been around since ancient Rome (*10*), no widely accepted definition of congestion exists to date as acclaimed by a conference of European Transport Ministers (*11*). Congestion has started to catch attention among transportation agencies in the United State since early 1980s. After massive transportation infrastructure development in the 50s and 60s, the supply of road capacity started to become insufficient to meet the demand in some areas.

In the early research and practice of estimating congestion, level of service (LOS) was often used to define congestion (*12*). The concept of LOS is well established in highway capacity analysis procedures (*13*). The levels range from LOS A, which represents free-flowing traffic, to LOS F, which represents forced flow or stop-and-go traffic. Urban roadways are typically considered satisfactory if operating at LOS D, which represents high-density but stable flow. Small increases in traffic at this level will often cause operational problems. Flow in the next level, LOS E, is said to be at capacity and on the verge of breaking down. A survey conducted in late 1980s (*12*) showed that although 90 percent of the transportation agencies incorporated the LOS concept in their congestion definition, there is no consensus regarding the beginning of congestion which corresponds to the congestion threshold. 45 percent defined LOS D or worse as congestion, whereas 20 percent and 14 percent defined LOS C and LOS E or worse, respectively.

In the first nationally accepted research on congestion, the National Cooperative Highway Research Program (NCHRP) report 398 (*14*), congestion was defined in two quantities: congestion and unacceptable congestion, described below:

- **Congestion** is travel time or delay in excess of that normally incurred under light or free-flow travel conditions.
- **Unacceptable congestion** is travel time or delay in excess of an agreed-upon norm. The agreed-upon norm may vary by type of transportation facility, travel mode, geographic location, and time of day.

This research recognized that past definitions of congestion fell into two basic categories, namely those focused on cause and those focused on effect. The authors believed that congestion measurement requires a definition that addresses the effect of congestion which is often shown by excess travel time and slow speed. It is clearly shown in the definitions that travel time was used as primary measure for congestion.

Lomax et al. (*14*) in the NCHRP report 398 defined congestion by two different sets of thresholds: the light or free-flow travel conditions and the “agreed-upon norm” for unacceptable congestion. They asserted that there is a need to separate the congestion and unacceptable congestion. The purpose of the separation is that the varying perceptions of congestion exist and a certain degree of congestion may have been expected by the travelers. Therefore, mobility improvement can be focused on the corridors or areas that fall below unaccepted congestion conditions.

In a more recent research about congestion and its extent (*15*), a survey was conducted among transportation professionals for congestion definition and measures. This survey revealed that measures such as travel time, speed, volume, and LOS are currently used as primary definitions of congestion for freeways. About half the responding agencies use travel time or speed as the measures for defining the congestion

(*15*), whereas 15 percent of the agencies use LOS for defining congestion. Comparing the results from the survey conducted in late 1980s (*12*) and the one in early 2000s (*15*), a declining trend of using LOS for defining congestion and increasing interests of using travel time and speed as measures for defining congestion are found.

Furthermore, recent research also found that the LOS concept is unable to define congestion. Some think that LOS fails to address the "saturated flow regime" (i.e., congestion) in a comprehensive fashion and the single LOS category ("F") in the HCM cannot capture the nature and extent of congestion (*16, 17*). The most recent 2000 edition of HCM has begun to look at the saturated flow regime. Researchers believe that more detailed measures than HCM-based LOS are required to capture the effect of operational strategies, which are often more subtle than capacity expansion projects.

In the National Transportation Operations Coalition's (NTOC) ITS technology forum, a question on "What should be our common definition of congestion" was raised (*18*). The responses to the question show that the inconsistency and lack of consensus among transportation practitioners. Most responses recognize two perspectives of the system and system users. From the system's perspective, transportation system is to provide transport to people and goods. Hence, congestion occurs when system productivity in terms of traffic flow is reduced. From the users' perspective, congestion occurs when average speed is below the optimal safe speed. The empirical evidence found that the optimal safe speed is typically around 60 mph for freeways. Since the maximum freeway flow occurs around 50 mph, most responses recognize the differences between the two perspectives.

What can be concluded from the congestion definitions in the previous research is that no matter what 1) category to focus on, whether the cause or the effect, 2) measure to use, whether the HCM LOS concept measure or the travel time-based measure, and 3) perspective to take, whether from system perspective or user perspective, congestion threshold is inevitably embedded in the congestion definition.

2.1.2 Measures of Congestion

Congestion measures are closely related to the definition of congestion. The measures quantify the amount of congestion based on the definition. Because different congestion definitions exist (e.g., the LOS-based or the travel time-based congestion definition), congestion measures were established according to the definitions. The congestion measures fall into two categories: the absolute measures and relative measures. The absolute measures are continuous and statistical-based (e.g., average travel time). The relative measures require a threshold or boundary value to begin the measurement (e.g., delay).

2.1.2.1 *Traditional measures*

Traditional measures of congestion are based on the Highway Capacity Manual (HCM) LOS concept. The HCM defines LOS on freeways with several traffic characteristics which include density and volume over capacity ratio (V/C). In the practice of congestion definition, a value of V/C is frequently used to set the beginning point of congestion (*12*, *19*) in lieu of density due to the relative easiness of traffic volume data collection. As with the LOS, the late 1980s survey (*12*) also revealed that there was no consensus on the V/C ratio corresponding to the congestion threshold. Of the agencies using the V/C ratio as a measure of congestion, 36 percent, 45 percent, and 19 percent defined the V/C ratio equal to or greater than 0.8, 1.0, and 1.25, respectively.

Measures of queue length and lane occupancy are sometimes used for estimating density. They are used by a small percent of transportation agencies (*12*) as measures to quantify congestion.

All above mentioned traditional measures can be used as congestion thresholds for quantifying congestion based on LOS concept.

2.1.2.2 *Travel time-based measures*

Travel time-based measures were established to quantify congestion defined by travel time. Several studies played an important role in developing the travel time based measures, which are introduced below.

1. NCHRP report 398 entitled "*Quantifying Congestion*" (*14*) was one of the early researches in recommending travel time-based measures for congestion. In the report, nine travel time-based measures were recommended, including:

    - ***Travel rate***. Travel rate, expressed in minutes per mile, is how quickly a vehicle travels over a certain segment of roadway. It can be used for specific segments of roadway or averaged for an entire facility. Estimates of travel rate can be compared to a target value that represents unacceptable levels of congestion.
    - ***Delay rate***. The delay rate is "the rate of time loss for vehicles operating in congested conditions on a roadway segment or during a trip" (*14*). This quantity can estimate system performance and compare actual and expected performance.
    - ***Total delay***. Total delay is the sum of time lost on a segment of roadway for all vehicles. This measure can show how improvements affect a transportation system, such as the effects on the entire transportation system of major improvements on one particular corridor.
    - ***Relative delay rate***. The relative delay rate can be used to compare mobility levels on roadways or between different modes of transportation. This measure compares system operations to a standard or target. It can also be used to compare different parts of the transportation system and reflect differences in operation between transit and roadway modes.
    - ***Delay ratio***. The delay ratio can be used to compare mobility levels on roadways or among different modes of transportation. It identifies the significance of the mobility problem in relation to actual conditions.

- ***Congested travel***. This measure concerns the amount and extent of congestion on roadways. Congested travel is a measure of the amount of travel that occurs during congestion in terms of vehicle-miles.
- ***Congested roadway***. This measure concerns the amount and extent of congestion that occurs on roadways. It describes the degree of congestion on the roadway.
- ***Accessibility***. Accessibility is a measure of the time to complete travel objectives at a particular location. Travel objectives are defined as trips to employment, shopping, home, or other destinations of interest. This measure is the sum of objective fulfillment opportunities where travel time is less than or equal to acceptable travel time. This measure can be used with any mode of transportation but is most often used when assessing the quality of transit services.
- ***The corridor mobility index***. This measure uses the speed of person movement value divided by some standard values. The speed of person movement is a "measure of travel efficiency that could be used to compare the person movement effectiveness of various modes of transportation" (*14*). It provides a way to compare alternative transportation improvements to traditional improvements such as additional freeway lanes.

All but one (travel rate) of the NCHRP report 398 recommended measures are relative measures. These relative measures need either the acceptable travel time or acceptable travel rate as the threshold to generate performance measure values.

2. The Texas Transportation Institute publishes the annual Urban Mobility Study for most urban areas with population above 500,000 in the United States (*2*). The study started in the early 1980s. During the course of over 20 years, many congestion measures were developed for the study. Some of the recently used measures are introduced below.

- ***Roadway congestion index***. This index allows for comparison across metropolitan areas by measuring the full range of system performance by focusing on the physical capacity of the roadway in terms of vehicles. The index measures congestion by focusing on daily vehicle miles traveled on both freeway and arterial roads.
- ***Travel rate index***. This index computes the "amount of additional time that is required to make a trip because of congested conditions on the roadway." It examines how fast a trip can occur during the peak period by focusing on time rather than speed. It uses both freeway and arterial road travel rates.
- ***Travel time index***. This index compares peak period travel and free flow travel while accounting for both recurring and incident conditions. It determines how long it takes to travel during a peak hour and uses both freeway and arterial travel rates.
- ***Travel delay***. Travel delay is the extra amount of time spent traveling because of congested conditions. The UMR study divided travel delay into two categories: recurring and non-recurring.

All of the above introduced measures are relative measures. The annual Urban Mobility Report used the free flow speed of 60 mph as the congestion threshold for freeways to calculate the above mentioned measures.

3. The recent study of Monitoring Mobility Program (MMP) concluded that travel time is the basis for defining mobility-based performance measures (*20*). Figure 2.1 shows that the travel time-based measures can be separated by the absolute measures and relative measures. This research introduced the following two new reliability indices:

- ***Buffer index***. The buffer index calculates the extra percentage of travel time a traveler should allow when making a trip in order to be on time 95 percent of the time. This method uses the 95th percentile travel rate and the average travel rate, rather than average travel time, to address trip concerns.

- ***Misery index***. The misery index represents the worst 20 percent of trips that occur in congested conditions. This index examines the trip reliability by looking at only the travel rate of trips that exceeds the average travel rate. This index measures how bad the congestion is on the days when congestion is the worst.

Although both LOS-based and travel time-based measures coexist in the practice, a recent study (*21*) revealed the trend of declining use of LOS-based and increasing use of the travel time-based measures. The Kentucky Transportation Center interviewed 13 focus states for their practices of measuring congestion and practices to mitigate congestion without building new capacity. One of the major findings regarding the measures of congestion is that the most popular measures are not LOS or V/C ratio but rather the direct measures of either average time to traverse the distance between two points, or the average speed of vehicles. The direct measures of average time or speed are used to construct estimates of delay during peak traffic periods.

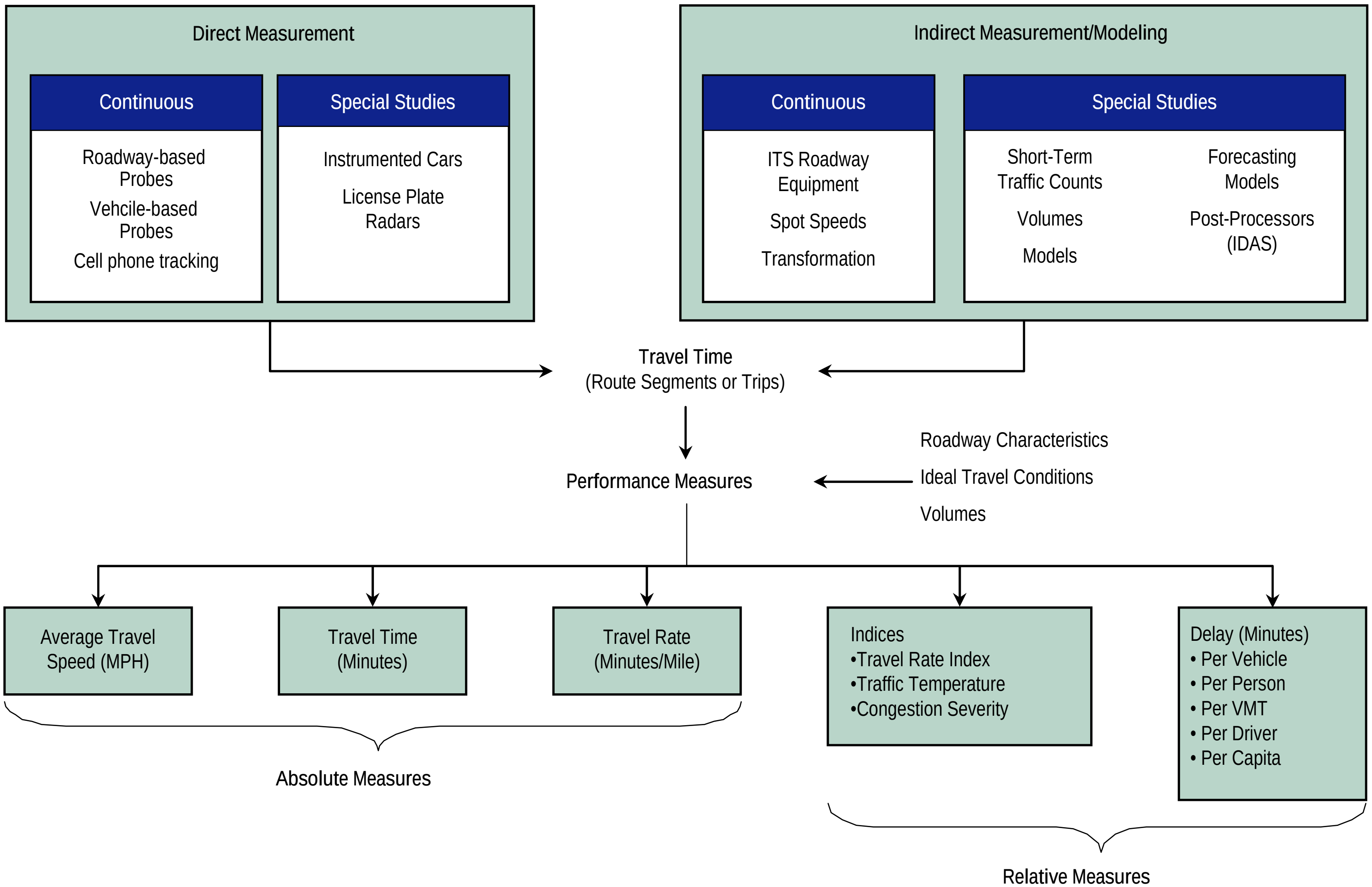


FIGURE 2.1 Travel time as the basis for defining mobility-based performance measures (*21*).

2.2 Freeway Performance Measures

Performance measures can be defined as indicators of transportation system effectiveness and efficiency – a practical way to measure progress toward objectives. Research shows that performance measurement is growing in importance and is becoming institutionalized within transportation agencies (*16*).

Freeways by definition are access-controlled highways that are characterized by uninterrupted traffic flow. Freeway performance refers primarily to congestion and mobility, particularly the quality of traffic flow or traffic conditions as experienced by users of the freeway (*16*). There are also measures related to other aspects of freeway performance, such as safety, operational efficiency, ride quality, environmental consequences and customer satisfaction, which is not within the scope of this research.

2.2.1 Freeway Congestion Measures for Planning and Investment Process

The uses of freeway congestion measures as part of the overall performance measures range widely from traditional traffic operations, engineering, and improvement studies to roadway and public transport alternatives analysis as well as a wide range of planning and policy evaluations (*14*). In some cases, congestion measures define policy objectives at an early stage of policy or system planning, and in other cases, they provide the basis for an annual congestion report on system conditions and performance as a communication and reporting tool. Figure 2.2 presents a general framework of a performance-based planning process that indicates how performance measures are used in the decision-making process (*21*). As shown, performance measures play a key role that influences several subsequent components such as data, analytical methods and strategies.

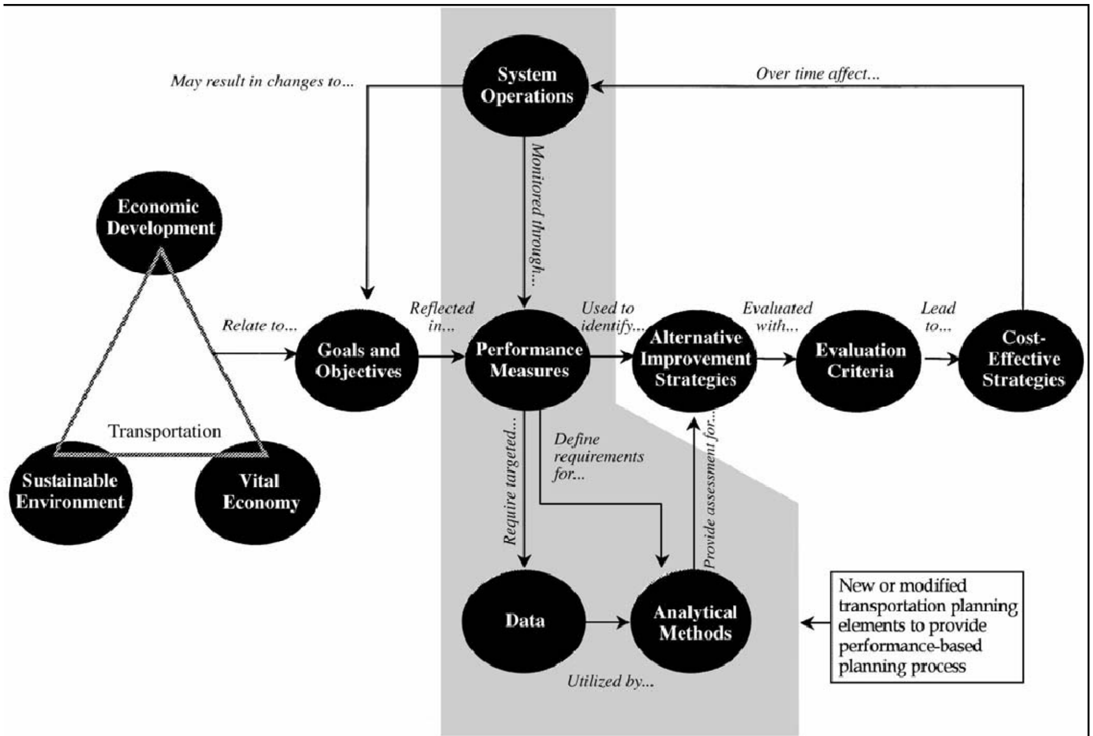


FIGURE 2.2 Typical performance-based planning process (*22*).

2.2.2 Components of Freeway Congestion Measures

The NCHRP 398 study (*14*) was one of the early research studies to introduce the four components interacting in a congested system (*14*). The four components are:

- Duration: amount of time congestion affects the travel system.
- Extent: number of people or vehicles affected by congestion, and geographic distribution of congestion.
- Intensity: severity of congestion.
- Reliability: variation of the other three elements.

To describe all aspects of congestion, the congestion measures need to cover the four components of congestion. However, the reliability component of the congestion was largely ignored in practice until recently. A recent NCHRP study (*16*) discovered that the concept of reliability is growing in importance. Many transportation agencies have begun to apply reliability measures as part of overall performance measures.

2.2.3 Current Practice and Recommended Core Freeway Congestion Measures

Many Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) have developed department-wide congestion measures. Freeway congestion measures are usually seen in their annual congestion reports in the form of summarized State or major metropolitan area level. A recent NCHRP study (*16*) has completed a comprehensive research on freeway performance measures. As a part of the research, benchmarking interviews were conducted with ten metropolitan areas on their practice of freeway performance measures. In the current practice of freeway congestion measures, the study found that

- For quality of service measures, derivatives of speed and delay are commonly used by both operating and planning agencies.
- The Travel Time Index is a popular metric. LOS as a metric is still in use in both planning and operations agencies, though it is not as widespread as it might have been 10 years ago.
- Reliability metrics have not yet found their way into a widespread use. However, consideration of travel time reliability is growing in acceptance, though its implementation is still problematic, primarily due to data requirements.

National level studies recommended performance measures for quantifying congestion. The National Transportation Operations Coalition (NTOC) conducted a Performance Measures Initiative (*23*) in 2004. The purpose of the initiative was to develop a few good performance measures for transportation operations. Although this initiative was designed for addressing a wide variety of governmental functions, the measures developed were highly relevant to quantifying congestion and characteristics.

The NCHRP research project 3-68 also recommended the core performance measures for all aspects of freeway performance (*16*). The top three performance measures recommended for quantifying typical congestion conditions are: travel time, Travel Time Index (TTI), and total vehicle delay. The two performance measures recommended for quantifying reliability are: Buffer Index and Planning Time Index (PTI). The NCHRP research project also specified whether a particular recommended performance measure has also been identified in the NTOC study. Table 2.1 is the recommended core freeway performance measures related to congestion and mobility from the NCHRP report.

2.3 Variations in Congestion Threshold

As reviewed in the above sections, most of congestion measures from either current practice or recommended freeway congestion measures are relative measures that depend on a congestion threshold to yield values. Many State Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) have developed their own thresholds for calculating the relative congestion measures. However, the thresholds are different in different areas.

The reasons why different areas use unique congestion thresholds may be threefold. First, some believe that free flow speed is not the most environmentally sustainable or economically efficient target for network capacity provision, and therefore, not a reasonable policy objective. Second, maximum flow occurs at speeds lower than free flow speed; some refer the point of maximum flow as maximum productivity. Third, most drivers may accept a certain level of congestion as long as any given trip could be completed safely within a reasonable and predictable time and with minimum interruption (*24*). Regardless of reasons, using unique thresholds would result in different values for congestion measures.

TABLE 2.1 Recommended Core Freeway Performance Measures (*16*)

Performance Metric	Definition	Units	Geographic Scale	Time Scale	Relationship to NTOC Measures
Average (Typical) Congestion Conditions (Quality of Service)					
Travel Time	The average time consumed by vehicles traversing a fixed distance of freeway	Minutes	Specific points on a section or a representative trip only; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak-periods, midday, daily	Direct correspondence to NTOC measure, but distinction between "link" and "trip" travel time is not used
Travel Time Index	The ratio of the actual travel rate to the ideal travel rate[a]	None; minimum value = 1.000	Section and areawide as a minimum; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak-periods, midday, daily	Not recommended by BTOC
Total Delay, Vehicles	The excess travel time used on a trip, facility, or freeway segment beyond what would occur under ideal conditions[b]	Vehicle-hours	Section and areawide as a minimum; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak-periods, midday, daily	NTOC distinguishes between recurring and nonrecurring delay; delay by source recommended by *Guidebook* as supplements
Total Delay, Persons	The excess travel time used on a trip, facility, or freeway segment beyond what would occur under ideal conditions[c]	Person-hours	Section and areawide as a minimum; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak-periods, midday, daily	NTOC distinguishes between recurring and nonrecurring delay; delay by source recommended by *Guidebook* as supplements
Delay per Vehicle	Total freeway delay divided by the number of vehicles using the freeway	Hours (vehicle-hours per vehicle)	Section and areawide	Peak hour, a.m./p.m. peak-periods; daily	Not recommended by NTOC
Spatial Extent of Congestion No. 1	Percent of Freeway VMT with Average Section Speeds <50 mph[d]	Percent	Section and areawide	Peak hour, a.m./p.m. peak-periods	NTOC uses a single measure with different thresholds, but the concept is fundamentally the same
Spatial Extent of Congestion No. 2	Percent of Freeway VMT with Average Section Speeds <30 mph	Percent	Section and areawide	Peak hour, a.m./p.m. peak-periods	
Temporal Extent of Congestion No. 1	Percent of Day with Average Freeway Section Speeds <50 mph	Percent	Section and areawide	Daily	NTOC uses a single measure with different thresholds, but the concept is fundamentally the same
Temporal Extent of Congestion No. 2	Percent of Day with Average Freeway Section Speeds <30 mph	Percent	Section and areawide	Daily	
Density	Number of vehicles occupying a length of freeway	Vehicles per lane-mile	Section	Peak hour/periods for weekday/weekend	Not recommended by NTOC
Reliability (Quality of Service)					
Buffer Index	The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time	Percent	Section and areawide	Peak hour, a.m./p.m. peak-periods, midday, daily	NTOC recommends a "buffer time" which is the difference between the 95th percentile travel time and the average; conceptually the same as the *Guidebook*
Planning Time Index	The 95th Percentile Travel Time Index	None; minimum value = 1.000	Section and areawide	Peak hour, a.m./p.m. peak-periods, midday, daily	

2.3.1 Current Practice in Congestion Thresholds

Current practice in congestion thresholds has been rather implicit. The congestion threshold used for performance measures are often found in the fine print of the transportation agencies annual congestion/mobility report without much explanation of why the specific threshold was used.

Two basic approaches exist for setting this congestion threshold. One common approach uses the "free-flow" or unimpeded conditions as the congestion threshold. Another approach uses target or "acceptable" conditions. Within each approach there are more than one means of defining the free flow or the "acceptable" condition. In the practice of setting the congestion threshold, the two primary approaches have their own advocates. Some believe that the free flow condition is more appropriate for comparisons in a national context, which represents "standard" or "ideal" conditions. On the other hand, the "acceptable" condition is more of a "target" value for key performance measures. This approach is useful when the focus is related to financially or physically constrained improvement programs (*14*, *15*).

2.3.1.1 *Free flow approach*

- 60 mph

  The national level Urban Mobility Report (UMR) (*2*) uses 60 mph as the free-flow condition for calculating congestion measures for freeways. The UMR uses several measured variables reported as part of the Highway Performance Monitoring System (HPMS) which is a program designed to assess the condition performance of the nation's highways annually. Speed estimations in UMR were based on these variables from HPMS. The limitation of using the HPMS data for congestion estimation is that the data can only reveal annual average estimation at an aggregated level.

- 85^{th} percentile off-peak speed

  The national level Mobility Monitoring Program (MMP) (*5*) uses 85^{th} percentile off-peak speed as the free-flow condition for calculating congestion measures.

The data from freeway sensors and monitors were used for MMP. Thus the speed distribution can be estimated and used for calculating congestion measures.

2.3.1.2 *Target approach*

- Maximum flow/productivity

  Minnesota Department of Transportation (MnDOT) defines congestion as traffic flowing at speeds less than or equal to 45 mph (*25*). The 45 mph threshold was selected since it is the speed where "shock waves" can propagate. These conditions also pose a higher risk of crash. MnDOT believes that although shock waves can occur above 45 mph, there is a distinct difference in traffic flow above and below the 45 mph level.

- Target value

  California Department of Transportation defines congestion as a condition where the average speed drops below 35 mph for 15 minutes or more on a typical weekday (*26*). In the 2004 Congestion Management System Report for the Boston Region Metropolitan Planning Organization (BRMPO) (*27*), the congestion threshold for limited-access roadways (freeway/expressway) was set at 50 mph. In the congestion management system report for the Nashville area NAMPO (*28*), the congestion threshold was set at a value less than or equal to 70% of free-flow speed for all roadways.

- Percentage of speed limit

  In the 2009 Annual Congestion Report by Washington State Department of Transportation (WSDOT) (*29*) congestion was estimated for average peak period travel speed below both 85% of posted speed limit and 70% of posted speed limit. WSDOT believes that the maximum throughput speed, where the greatest number of vehicles can occupy the highway at the same time; usually occurs at between 70% and 85% of posted speed limit. For a measure of total delay, 50 mph is used for the threshold, and for determining the duration of the congested period, 45 mph is used.

2.3.2 Current Research in Congestion Thresholds

The limited research that has been conducted on the congestion threshold issue focused on policy debates (*30*) and operational problems. No research has been conducted to date on the effect of congestion thresholds on performance measures and, in turn, transportation policy and investment decision making.

The recent NCHRP research was one of the few studies that pointed out the congestion threshold issue (*16*). As shown in Table 2.1, when recommending the core performance measures for typical congestion conditions, the research team used both 50 mph and 30 mph as thresholds for the spatial and temporal extent measures. The reason that the research team used the two threshold values is that the 50 mph is generally the boundary between free and congested flow (i.e., the speed at freeway capacity) and 30 mph was chosen to capture flow that is truly in the saturated regime. The research pointed out that the relative measures "have the advantage of being easily explained but since they are binary (either a measurement is in the range or it isn't), they can be insensitive to subtle changes in the underlying phenomenon" (*16*). Although the research pointed out the issue, no further research has been performed on the congestion thresholds.

Both the NCHRP research (*16*) and another research study by the Texas Transportation Institute (*31*) discussed the issue of using the speed limit as the congestion threshold to establish the free flow condition. This practice has two potential problems when the actual free flow speed (which can be obtained from the 85th percentile speed that occurs under the light traffic condition) is higher than the speed limit. First, using the speed limit as the threshold would underestimate the magnitude of congestion. Second, using the actual free flow speed as the threshold would post an "illegal" problem. The NCHRP study recommended using the lower of the two speeds (the actual free flow speed or the speed limit) even though the research acknowledged that this approach would miss a "small" amount of delay if the free flow speed is higher than the speed limit.

2.4 Data Issues for Congestion Estimation

Most data available for mobility performance monitoring purpose are originally collected for purposes other than monitoring freeway mobility performance (*16*). Therefore, the data must be extracted from the data collecting systems to compute congestion measures. Also, extensive manipulation of raw data must be performed to produce the desired information. The review of the data issue of this study focuses on the needs of travel time-based measures.

2.4.1 Data Source for Travel Time

Three basic travel time data collection approaches include 1) floating car or other vehicle-based sampling procedures, 2) traffic operations center archives, and 3) estimation or modeling techniques (*31*). Each of these approaches has its advantages and limitations for congestion estimation. The first two approaches collect real-world data as opposed to the third approach using simulation data.

2.4.1.1 *Traffic operation center archives*

Collecting traffic information from fixed sensors and monitors has been the state of the practice in urban areas around the U.S. Traffic operations center archives are the data archives that storage continuously collected data from field sensors. Until recently it has been difficult to use this approach to incorporate real-time intelligent transportation system (ITS) data due to complexities in data formats and storage. The Mobility Monitoring Program (MMP) is such a data collection effort by the Federal Highway Administration (FHWA) to track and report traffic congestion and travel reliability using archived ITS data on a national scale. The MMP started in 2001. By the end of the 2004, nearly 30 cities and 3,000 freeway miles were covered by the MMP (*5*).

Due to the high cost of purchase, installation, and maintenance of the sensors as well as the complexities in data formats and storage, sensors and collected traffic information are available only at certain locations of freeways. The drawback of ITS sensor data for calculating congestion measures is that the equipment does not measure travel time directly, the collected spot speeds must be converted to travel time for congestion measure calculation.

2.4.1.2 *Probe vehicle sample data*

With the growing interests in real time and low cost traffic information, collecting traffic data through probe vehicle technique has become the state of the art in recent years. Although the probe vehicle data collecting technique has been around for over thirty years (*32*), only until recent years with the advances in wireless communication systems and global positioning system (GPS) sensors the technique gained feasibility and popularity. There are five types of commonly used probe vehicle data collection systems in the U.S. (*33*). Below are brief descriptions of these systems from the Travel Time Data Collection Handbook (*33*).

- ***Signpost-Based Automatic Vehicle Location (AVL).*** This technique has mostly been used by transit agencies. Probe vehicles communicate with transmitters mounted on existing signpost structures.
- ***Automatic Vehicle Identification (AVI).*** Probe vehicles are equipped with electronic tags. These tags communicate with roadside transceivers to identify unique vehicles and collect travel times between transceivers.
- ***Ground-based Radio Navigation.*** Often used for transit or commercial fleet management, this system is similar to the global positioning system (GPS). Data are collected by communication between probe vehicles and a radio tower infrastructure.
- ***Cellular Geo-location.*** This experimental technology can collect travel time data by discretely tracking cellular telephone call transmissions.
- ***Global Positioning System (GPS).*** Probe vehicles are equipped with GPS receivers and two-way communication to receive signals from earth-orbiting satellites. The positional information determined from the GPS signals is

transmitted to a control center to display real-time position of the probe vehicles. Travel time information can be determined from the collected data.

Recent development of probe vehicle technology has been in the cellular geo-location and GPS systems. The other three of these five systems have limitations in their applications. AVL and ground-based radio navigation systems are used primarily for small-scale transit management purposes. The AVI or tag system requires infrastructure for the fixed transceivers and its primary application is for electronic toll collection. The Houston metropolitan area is one of the few metropolitan areas in the U.S. that has a majority of the freeways covered by the AVI tag system, although only a small portion of the freeway system is actually toll way.

Clearly, the emerging probe vehicle technique is a method to directly measure travel time. However, the technology also has drawbacks. Some of the probe vehicle data suffers from extremely small samples. In addition, since many performance measures require traffic volumes, additional collection effort is required to develop the full suite of performance measures (*16*, *20*).

2.4.2 Fixed Sensor Data for Congestion Measures

Using the data collected by the fixed sensors in the form of traffic operation center archives for freeway performance measure has been the practice in recent years. Because of the detailed nature of the archived operations data, issues and challenges are associated with the data processing.

2.4.2.1 *Data quality control*

The quality of archived data from traffic operation centers varies by their source (*5*). In practice and research, quality rules have been established to control the data for performance monitoring uses (*5*). However, there are no universally applied rules available to date. Some rules may be based on concepts or theory, such as highway capacity or traffic flow, while other rules may be based on empirical experiences (*16*).

2.4.2.2 *Data aggregation*

Both spatial and temporal aggregation is necessary for performance monitoring and evaluation purpose. The levels of aggregation depend upon the purpose of the performance measures. The full range of spatial scale as described in the NCHRP research project 3-68 is listed below (*16*).

- **By Lane** (point location);
- **By Direction** (point location), all functional lanes combined – this is sometimes referred to as a "station;"
- **Link –** Typically between access points or entrance and exit ramps;
- **Section or Segment –** A collection of contiguous links;
- **Corridor –** Several sections/segments that are adjacent and travel in approximately parallel directions (e.g., freeway and arterial street, arterial street and rail line);
- **Subarea –** A collection of several sections or corridors within defined boundaries; and
- **Area wide/Regional –** A collection of several sections or corridors within a larger political boundary.

The temporal periods considered for performance evaluation in the NCHRP research project 3-68 are (*16*):

- **Peak hour** (based on maximum volume);
- **Peak hour** (based on minimum speed or maximum delay);
- **Peak period** (to encompass typical commuting times that include most delay);
- **Mid-day or overnight**;
- **Daily or sum totals** (to encompass all delay); and
- **Weekday versus weekend**.

Two different methods exist when selecting peak hour for the worst performance monitoring. The HCM defines the peak hour as the hour with the highest volumes. The hour defined by the HCM concept typically yields the hour just before the freeway breaks down (*16*). And the hour with the lowest speeds typically lags the hour with the highest volumes (*16*).

The consideration for selecting length of peak period for performance monitoring is that the peak period should be long enough to encompass the growth in traffic; thus, "peak periods will typically include the free-flow traffic on either side of the peak traffic shoulders" (*16*).

Two important steps in both spatial and temporal aggregation procedure are 1) using volume as the weighting factor for average speed aggregation and 2) factoring up incomplete volume statistics to account for missing data (*16*). Both steps are essential to capture the whole picture of freeway performance (*5*, *16*).

2.4.2.3 *Transforming spot speeds to travel times*

Two basic methods are currently used to estimate freeway travel times using the spot speeds/link travel time: the "snapshot" method and the vehicle trajectory method (*16*). "The snapshot method sums all link travel times for the same time period, regardless of whether vehicles traversing the freeway section will actually be in that link during the snapshot time period" (*16*). The assumption of the snapshot method is that the link travel times are constant for the entire duration of the vehicle trip. "Because of this assumption, the snapshot method underestimates section travel time when traffic is building and overestimates section travel time when traffic is clearing" (*16*).

"The vehicle trajectory method "traces" the vehicle trip in time and applies the link travel time corresponding to the precise time in which a vehicle is expected to traverse the link" (*16*). The vehicle trajectory method attempts to closely model the actual link travel times as experienced by the motorists. In practice, however, the snapshot method is often used in both real-time applications and situations when a significant amount of data processing is needed because of its simple calculation (*5*, *16*).

2.4.2.4 *Accuracy of spot speed for travel time*

Studies have found that both sensor location and sensor spacing affect the accuracy of using the spot speed for estimating travel time (*16, 34*). The NCHRP study (*16*) asserts if the sensors are installed in locations of free flow such as the downstream of a bottleneck, speeds measured at a single point may not be representative of speeds along the full length of the link. For a similar reason, widely distributed sensor spacing may not adequately represent the full range of speed variation on the link. The long sensor spacing would introduce a greater error especially if the snapshot method is used for estimating travel time. This is because under the assumption of the snapshot method that travel times between two consecutive sensors are constant for all vehicles traversing on the link. The longer the sensor spacing is, the less accurate this assumption becomes.

Several field studies have been conducted to determine whether the travel time converted from spot speed falls within acceptable limits. The field test done in Virginia resulted in significant error in travel time differences (*35*). A study used the MMP data from Cincinnati and Atlanta to perform the effect of sensor spacing on performance measure (*34*). In the analysis, the actual sensor spacing was used as the baseline. Tests were run by deleting sensors for higher sensor spacing. The results showed that when sensor spacing was increased relative to the baseline sensor spacing, error was introduced into congestion measures. However, the errors varied depending on the locations of the sensors. Sometimes one spacing pattern overestimated the congestion measures and other times underestimated the congestion measures. Further analysis showed that strategic location of sensors could improve the error rate versus the same spacing for orderly deletion of sensor.

2.4.3 Probe Vehicle Data for Congestion Measures

Using the probe vehicle data for performance measures has started to gain popularity in recent years due to the development of probe vehicle technology in the cellular geo-location and GPS systems. Nevertheless, data from all probe vehicle technologies have similar characteristics when used for performance measures.

2.4.3.1 *Accuracy and limitations*

The accuracy of probe vehicle data for performance measures is largely dependent on two factors: the time spacing of probe vehicles and the total number of probe vehicle runs (*16*). The accuracy increases as the numbers of probe vehicles increase and the time spacing between the runs is reduced (*16*).

Although probe vehicle data has been used in many transportation application areas, such as traffic management, traveler information, and system mobility measures, no industry wide standard has been developed to evaluate the reliability and accuracy of the data. Many research studies and deployments have developed their own specifications for evaluating data quality (*36, 37*). Data quality is a concern when using probe vehicle data for performance measures calculation.

Another limitation of using probe vehicle data for performance evaluation is the lack of volume data. As introduced in fixed sensor aggregation, volume is used as the weighting factor for congestion measures throughout the aggregation process. Without the volume data, only a few measures can be calculated.

This research will improve on these past studies in several important areas. First, a comprehensive system wide data from both fixed sensor and probe vehicle AVI technology was gathered. In addition to the different data collection technology, this research included data from a variety of real-world travel time distributions. Third, the congestion threshold in general and the specific effect of freeway congestion thresholds on transportation investment decision-making inputs was studied the first time. The following chapter discusses these improvements and overall research approach in detail.

CHAPTER III
RESEARCH APPROACH

This chapter presents the basic research approach developed to investigate the effects of congestion threshold on performance measure which is the input for decision-making. The research problem concerning congestion threshold is introduced, followed by research objectives and hypotheses. Finally, analysis techniques, procedures as well as related statistical analysis are described. This discussion provides the basis for the data collection and data processing procedures, which will be addressed in the next chapter.

3.1 Problem Statement and Research Objectives

Congestion and how it is measured has been studied for decades. "When does congestion start?" is still a question being debated among researchers today. The two basic approaches include using 1) free-flow or 2) some target condition as congestion threshold. By choosing a different approach, congestion measure could yield very different results. Within the two basic approaches, there are also various means of defining and quantifying congestion. Each approach has its advantages and disadvantages, and could be chosen for specific interests. Particularly, the inconsistency in congestion measures complicates investment decision-making for transportation projects.

At the national level, if performance measurement is taken to an extreme, allocation of federal funding faces the challenge of selecting the most congested regions. An obvious issue is that the congestion measures that state transportation agencies and planning organizations submitted are not comparable due to different thresholds or approaches used. Another issue is that some nationwide congestion studies such as the Urban Mobility Report (UMR) and the Mobility Monitoring Program (MMP) use the same threshold to quantify congestion for all regions; however, many researchers do not believe that the congestion should be evaluated under the same threshold for all regions due to the acceptance of a certain level of congestion in some severely congested regions.

At regional and local levels, many transportation agencies use performance measures to help screen projects or set project priorities in the development of their transportation improvement program (TIP). In addition, many agencies have begun to use performance measures to help guide resource allocation decisions at the program level in the system planning and programming process (*9*). What has not been determined, however, is the role of a congestion threshold speed. For example, would a different set of projects chosen if 60 mph or 35 mph was used as the beginning of congestion? Investment decision is once again jeopardized by the congestion threshold at regional and local level.

At the freeway and corridor level, the issue becomes more complicated because travel time per mile is distributed differently for different highway segments. Causes of different travel time distributions include traffic demand variability, geometric design, surrounding land use and demographics, availability of traffic management or Intelligent Transportation Systems (ITS) facilities such as dynamic message signs or surveillance cameras, and so on. Different travel time distributions can result in different performance measures.

Figure 3.1 illustrates examples of different travel time distributions. Curve A could be a travel time distribution of a freeway segment in a small urban area where travel time peaks fast for a relatively short amount of time. Curve C could be a travel time distribution for a freeway segment in the Central Business District (CBD) of a large urban area where travel time peaks for a longer period of time. Curve C has a form of a plateau, however, does not have a sharp summit. Curve B is somewhere in between Curves A and C, and could be a freeway segment in a suburban area where peak period is shorter than in a large urban area, and peak travel time is less pronounced than in a small urban area.

Figure 3.1 also illustrates the complication of different threshold approaches. For the congestion threshold that uses a free flow speed approach (such as threshold example

1 which uses the speed limit), all three travel time distributions have equal travel time delay although road segment A and B have shorter congested periods, however, more pronounced distributions. On the other hand, for the threshold set at a lower speed, i.e., a longer travel time (such as threshold example 2), Curve C would not be considered congested at all.

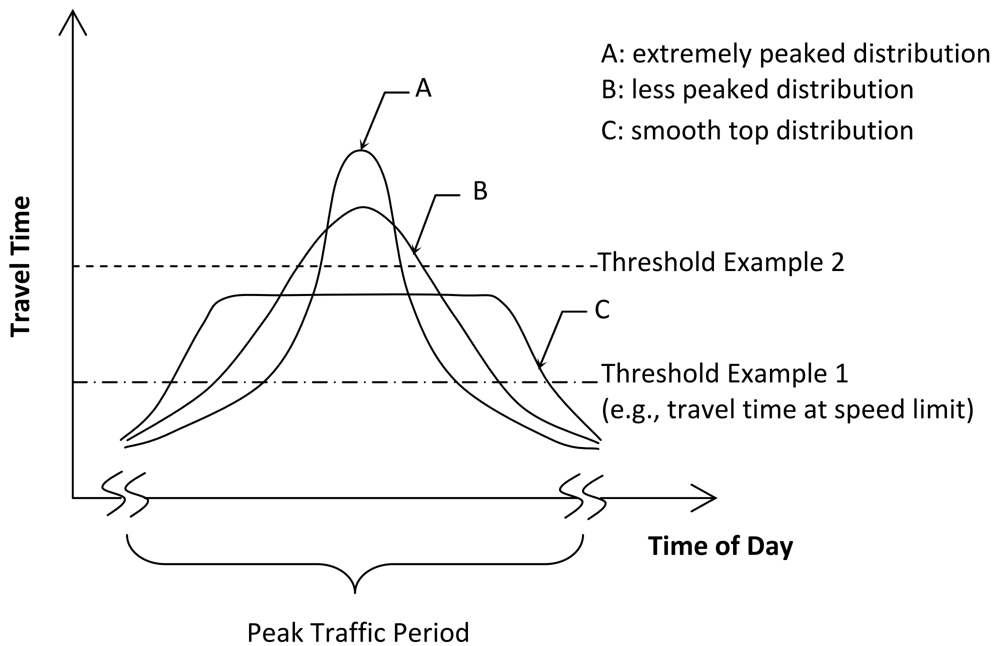


FIGURE 3.1 Travel time distribution examples.

Nationally, regionally as well as locally, policy discussions about the scale of the congestion problem and the need for solutions may be side-tracked by this threshold issue. The limited research that has been conducted on this issue focuses on operational problems or policy debates. Current understanding of the impact of the congestion threshold is at the anecdotal level in many areas and may not provide enough support for critical decision-making in project investment.

This research investigates the effect of freeway congestion thresholds on congestion performance measures. Three specific objectives are described as follows.

The first objective is to examine the changes in rankings of congestion measures for freeway segments when different congestion thresholds are used. This objective involves 1) ranking freeway segments under a whole spectrum of thresholds using the selected congestion measures, 2) examining the ranking changes for freeway segments along the spectrum of thresholds, and 3) evaluating the differences in ranking for statistical significance and detecting the particular threshold, if any, which would change the relationship in terms of statistical significance. Findings from this objective can provide decision makers with information about effects of congestion thresholds on transportation project selection and prioritization and, in turn, help investment decisions.

The second objective is to estimate or predict delay as a function of congestion threshold. Delay is one of performance measures widely used for measuring congestion. According to its definition, delay is measured as the additional vehicle travel time that is greater than the vehicle travel time at the predetermined congestion threshold. Delay changes accordingly if a predetermined congestion threshold is changed. Findings from this objective can provide a basis for comparisons between areas. This objective involves 1) investigating whether a relationship exists between delay under different congestion thresholds, and 2) finding the relationship in order to estimate change of delay due to change of congestion thresholds. One challenge that is sometimes faced by decision makers or transportation economists is to determine how much of the change in a delay is due to the changes of congestion threshold, and whether the relationship is linear.

The third objective of this research is to examine whether the change of speed limit affects travel time distribution and, in turn, the congestion measure result. Because many urban areas use the speed limit or percentage of speed limit as the congestion threshold (*28*), findings from this objective can provide decision makers with information on the sensitivity of travel time distribution to speed limit, and discover how appropriately the speed limit can be used as the congestion threshold.

3.2 Research Questions and Hypotheses

To achieve the three research objectives, three corresponding research questions and associated hypotheses are described as follows.

1. Do rankings of congestion measures for freeway segments hold steady across different congestion thresholds? Are there situations where a change in threshold value would change the congestion ranking of a set of freeways?

Hypothesis 1: There is no difference between the rankings of congestion levels on freeway sections using different congestion thresholds.

2. What is the relationship between delay and congestion threshold? As the congestion threshold is changed (for example by 5 mph), how does delay change? Is the relationship linear?

Hypothesis 2: The relationship of delay under different congestion thresholds is non-linear and can be expressed in a quadratic form.

3. Is speed limit one of the factors that affect travel time distribution?

Hypothesis 3: Speed limit has an effect on off-peak travel time distribution and speed limit has no effect on peak period travel time distribution.

3.3 Analysis Procedures

The analysis procedures outline how the three research objectives were accomplished as well as how the three corresponding hypotheses were tested.

This research uses an empirical approach as opposed to a simulation-based experiment to conduct the research. The reasons for a empirical approach are 1) a large amount of empirical data that is available and proven to be reliable (*5*, *16*); 2) time and money constraints to simulate a large amount of continuous travel time data that is necessary for the research; and 3) the simulated outcomes may differ from actual outcomes due to simplified assumptions, i.e., human behavior, in the simulation methodologies.

Since it is not possible to collect data from all road segments for the analysis; and even for this relatively small study, strict control of all factors influencing travel time distribution was not achievable and not all factors could be identified. Therefore, quasi-experiments were used to perform the analysis.

Experimental design is a study design used to test cause-and-effect relationships between variables. The classic experimental design specifies an experimental group and a control group. The independent variable is administered to the experimental group and not to the control group, and both groups are measured on the same dependent variable. Subsequent experimental designs have used more groups and more measurements over longer periods. True experiments must have control, randomization, and manipulation.

Compared to a true experiment, a quasi-experiment lacks full control over the events and subjects being studied, in terms of random assignment of treatments to subjects (*38*). The advantage of the quasi-experimental design is that it requires less manipulation of the phenomena being studied, which in turn increases both the range of its application and the generalizability of the findings it produces. However, at the same time, it makes it more difficult to rule out extraneous influences on the behavior being studied (*39*).

The analysis procedure is divided into three primary components which relate to the three research hypotheses.

3.3.1 Hypothesis 1

Freeway sections were selected to test the hypothesis. The consideration for selection of freeway sections was to represent a variety of traffic and land use patterns. The analysis period was the year of 2006. The reason of using one entire year as the analysis period was to minimize the possibility of potential confounding factors such as seasonality.

The approach was 1) calculating the congestion measures for the selected freeway sections under a spectrum of congestion thresholds, 2) ranking freeway sections for each congestion threshold scenario using the congestion measures calculated with those thresholds, 3) examining and evaluating the ranking changes of freeway sections under various threshold scenarios for statistical significances.

3.3.1.1 *Analysis techniques*

A cross-sectional study approach was used to test this hypothesis. Cross-sectional studies (also known as cross-sectional analysis) form a class of research methods that involve observation of some subset of a population of items all at the same time.

A variety of important factors were considered in selecting study sites. The purpose of considering these factors is to ensure that the experiment performed cover a range of conditions by the data. The consideration also helps to validate the findings and rule out the possibility of extraneous influences by showing the variety of factors and conditions covered. The factors are explained below.

- Both area size and area type were considered as factors which may influence travel time distribution. Large and more populated metropolitan areas are typically more congested and have a longer period of congestion than the small and less populated areas.
- AADT/C ratio was used as a general measure of congestion level to ensure that roadways at all congestion levels are considered in the analysis. "AADT" is the Annual Average Daily Traffic. "C" is the two-way hourly capacity. This ratio was found to be highly correlated to the volume to capacity ratio (V/C ratio) that is also used to indicate traffic pressure or demand level (*40*). The volume in the V/C ratio is, however, an hourly flow rate. Therefore, the AADT/C is a better indicator for cases where congestion occurs several hours a day.

- Number of lanes per direction is an indicator of the study section capacity. The changes in the freeway capacity which can be viewed as supply of the freeway system will influence the travel time distribution with the demand being the same.
- According to the Highway Capacity Manual (*13*), the percentage of trucks on the freeway section will significantly affect the service flow rate of the section. The service flow rate will in turn influence travel time distribution of the section.
- The proximity to major bottleneck is also believed to influence the travel time distribution. If a bottleneck (e.g., freeway-to-freeway interchange) is immediately downstream of the study section, queues are likely to form routinely on the study section. It is therefore important to note the proximity of the bottleneck.
- The weaving area is formed when an on-ramp is closely followed by an off-ramp (*13*). Shorter ramp spacing would create more frequent weaving areas, which in turn would influence the flow rate and travel time distribution.
- The speed limit is a factor influencing travel time during the free flow driving condition. However, whether the speed limit affects the travel time distribution during the congested condition will be tested by this research.

3.3.1.2 *Selected performance measures*

Three performance measures were selected for the analysis based on effectiveness and popularity of their use for congestion evaluation purposes (*16*). The formulation and use of the measures are described as follows.

1. Delay

   The total delay is used to measure congestion magnitude. Delay was originally defined as the additional vehicle travel time that is greater than the free flow vehicle travel time (*14*). However, as reviewed by this research in the Background section, travel time under various traffic flow conditions were used in practice for delay calculation. Therefore, the total segment delay is formulated in Equation 3.1 using a reference travel time in place of the free flow travel time. It can be reformulated with a congestion threshold in Equation 3.2. It can be seen from Equation 3.3 that the total delay divided by segment length is a function of congestion thresholds.

$$\underset{(vehicle-minutes)}{Total\ Segment\ Delay} = \left[\underset{(minutes)}{Actual\ Travel\ Time} - \underset{(minutes)}{Reference\ Travel\ Time}\right] \times \underset{(vehicles)}{Vehicle\ Volume} \qquad \text{Equation 3.1}$$

$$\underset{(vehicle-hours)}{Total\ Segment\ Delay} = \left[\frac{Segment\ length\ (miles)}{Average\ speed\ (mph)} - \frac{Segment\ length\ (miles)}{Congestion\ threshold\ speed\ (mph)}\right] \times \underset{(vehicles)}{Vehicle\ Volume} \qquad \text{Equation 3.2}$$

$$\underset{(vehicle-hours/mile)}{\frac{Total\ Segment\ Delay}{Segment\ length}} = \left[\frac{1}{Average\ speed\ (mph)} - \frac{1}{Congestion\ threshold\ speed\ (mph)}\right] \times \underset{(vehicles)}{Vehicle\ Volume} \qquad \text{Equation 3.3}$$

2. Travel Time Index (TTI)

   TTI is used to measure congestion intensity. It is the ratio of time spent in traffic during peak traffic times as compared to free flow traffic times. For example, a TTI value of 1.2 indicates that for a 15-minute trip in free flow traffic, the average travel time for the trip is 18 minutes (15 minutes × 1.20 = 18 minutes), which is 20 percent longer than free-flow travel time. The formulation of TTI is presented in Equation 3.4. If speed is used in calculation, TTI can also be reformulated with congestion thresholds in Equation 3.5. Equation 3.5 shows TTI is also a function of congestion thresholds.

$$TTI = \frac{Average\ travel\ time\ (minutes)}{Reference\ travel\ time\ (minutes)}$$ Equation 3.4

$$TTI = \frac{Congestion\ threshold\ speed\ (mph)}{Average\ travel\ speed\ (mph)}$$ Equation 3.5

3. Planning Time Index (PTI)

   PTI is used to measure congestion reliability. The planning time index represents the total travel time that should be planned when an adequate buffer time is included. The planning time index compares near-worst case travel time to a travel time in light or free-flow traffic. For example, a planning time index of 1.60 means that for a 15-minute trip in light traffic, the total time that should be planned for the trip is 24 minutes (15 minutes × 1.60 = 24 minutes). The planning time index is useful because it can be directly compared to the travel time index (a measure of average congestion) on similar numeric scales (*5*). The planning time index is computed as the 95th percentile travel time divided by the free-flow travel time (Equation 3.6). It can also be formulated as a function of TTI (Equation 3.7). Since PTI is a function of TTI and TTI is a function of congestion thresholds and average travel speed, PTI is, therefore, a function of congestion threshold.

$$PTI = \frac{95^{th} percentile\ travel\ time\ (minutes)}{Reference\ travel\ time\ (minutes)}$$ Equation 3.6

$$PTI = \frac{Congestion\ threshold\ speed\ (mph)}{95^{th} percentile\ travel\ speed\ (mph)}$$ Equation 3.7

3.3.1.3 *Congestion threshold scenarios*

Eight congestion threshold scenarios were identified based on current practices as introduced in Chapter II, and the need to discover the trend which may exist. Two different congestion threshold setting approaches were tested. The uniform approach was to use a single threshold for all road segments. A non-uniform approach was to use different thresholds for different road segments based on a predetermined criterion.

Seven uniform congestion threshold speed scenarios and one non-uniform threshold scenario were selected. The congestion threshold speeds used for the non-uniform scenario were based on the location of the freeway segments. In the real-world situation, the freeway sections located in the Central Business District (CBD) area typically have a lower speed due to the high traffic. In addition, a certain degree of congestion in the CBD area is expected by the general public. On the other hand, the freeway sections located in a less urbanized area typically have a higher speed due to the low traffic. Higher driving speed and little congestion is typically expected by the general public for this area type.

The eight congestion thresholds scenarios are:

- Scenario 1: 60 mph
- Scenario 2: 55 mph
- Scenario 3: 50 mph
- Scenario 4: 45 mph
- Scenario 5: 40 mph
- Scenario 6: 35 mph
- Scenario 7: 30 mph
- Scenario 8: 35 mph in CBD, 45 mph in Urban, 55 mph in Suburban, and 60 mph in Rural

3.3.1.4 *Statistical analysis*

A linear regression statistical analysis was used to test null hypothesis 1. One method to test whether two ranking values obtained under two different congestion thresholds are equal is to test whether the two sets of values fit a linear line of Y=X. This linear line Y=X is a special form of the general linear model illustrated in Equation 3.8.

$$Y = \beta_0 + \beta_1 X + \varepsilon \qquad \text{Equation 3.8}$$

where:

β_0 = intercept

β_1 = slope

ε = random error term with mean of 0 and a constant variance.

The linear line of Y=X is the special form when no intercept is in the model (β_0=0) and the slope of the line is equal to 1 (β_1=1). Therefore, testing the hypothesis 1 can be viewed as testing whether the relationship of the two sets of ranking values fit the general linear model with no intercept and slope equals to one. An α value of 0.05 was selected for the analysis.

Using the 60 mph as the base case scenario rankings, null hypothesis 1 can be illustrated by a mathematical form in Equation 3.9:

$$R_i^m = \beta R_{60}^m + \varepsilon$$
$$H_{01:}\ \beta = 1 \qquad \text{Equation 3.9}$$

where:

R = congestion rankings for freeway segments;

m = selected performance measures (i.e., delay, TTI and PTI) as introduced in section 3.3.1.2;

i = congestion thresholds scenarios ranging from 55 mph to 30 mph with 5 mph increment;

R_i^m = congestion rankings using performance measure *m* under congestion threshold scenario *i* mph;

R_{60}^m = congestion rankings using performance measure *m* under congestion threshold scenario 60 mph;

ε = random error term with mean of 0 and a constant variance, and

β = unknown regression coefficient.

3.3.2 Hypothesis 2

Freeway sections were selected to test the hypothesis. As hypothesis 1, the consideration for selection of freeway sections was to represent a variety of traffic and land use patterns. The analysis period was the year of 2006. The entire year was selected as the analysis period was to minimize the possibility of potential confounding factors such as seasonality.

The approach was 1) calculating the congestion measures for the selected freeway sections under a spectrum of congestion thresholds, 2) examining the relationship of the congestion measures under various congestion threshold scenarios, and 3) evaluating whether the relationship is non-linear and can be expressed in a quadratic form.

3.3.2.1 *Analysis techniques*

A cross-sectional approach was used to test this hypothesis. The same important factors as hypothesis 1 are considered in selecting study sites. The study sites used in the hypothesis 1 can be used for testing hypothesis 2.

3.3.2.2 *Selected performance measures*

To adjust the difference caused by segment length variation, delay divided by the segment length (Equation 3.3) was used as the measure for hypothesis 2. The reason that the Travel Time Index and Planning Time Index were not used for the hypothesis testing is that the relationship of these two measures under various threshold scenarios can be easily obtained mathematically because speed is the only variable in both measures.

3.3.2.3 *Analysis scenarios*

Delay per mile at congestion threshold of 60 mph was used as the base case for regression. The following regression scenarios were performed.

- Delay per mile obtained using congestion threshold of 55 mph vs. 60 mph
- Delay per mile obtained using congestion threshold of 50 mph vs. 60 mph
- Delay per mile obtained using congestion threshold of 45 mph vs. 60 mph
- Delay per mile obtained using congestion threshold of 40 mph vs. 60 mph
- Delay per mile obtained using congestion threshold of 35 mph vs. 60 mph
- Delay per mile obtained using congestion threshold of 30 mph vs. 60 mph

3.3.2.4 *Statistical analysis*

A regression analysis was used to test null hypothesis 2. One method to test whether two values of delay per mile obtained under two different congestion thresholds have a non-linear relationship is to fit the two values to a quadratic line and test whether the quadratic coefficient of the quadratic equation is equal to 0. If the quadratic coefficient is not equal to 0 and the quadratic line fits the data well, the two values have a non-linear quadratic relationship. If the quadratic coefficient is equal to 0, the two values have a linear relationship.

Using 60 mph as the base case scenario, null hypothesis 2 can be illustrated by Equation 3.10:

$$D_i = \alpha + \beta D_{60} + \gamma\, D_{60}^2 + \varepsilon$$
$$H_{02:}\, \gamma = 0 \qquad \text{Equation 3.10}$$

where:

D_i = delay per mile obtained using an alternative congestion threshold scenario other than 60 mph (1,000 vehicle hours/mile);

D_{60} = delay per mile obtained using 60 mph congestion threshold (1,000 vehicle hours/mile);

α = constant term;

β = linear coefficient;

r = quadratic coefficient; and

ε = random error term with mean of 0 and a constant variance.

3.3.3 Hypothesis 3

A historic event was used to test this hypothesis. Before May 2002, freeway speed limits in the Houston metropolitan area ranged from 60 mph to 70 mph. In May 2002, the speed limits for freeways were lowered to 55 mph area wide for environmental reasons. However, in September the speed limits were raised back to a speed limit that is 5 mph lower than the pre May 2002 speed limit. Hypothesis 3 was tested by examining the speed distribution trend of the before, during and after periods of the event.

The approach was 1) exploring the trend of speed distribution and travel growth for the study sections in the "before," "during" and "after" periods, 2) comparing the differences between the trends of speed distribution and travel growth at the time of speed limit change or the "during" period, 3) identifying rival events or ruling out the confounding factors, and 4) drawing conclusions on whether the speed limit change resulted in a change in the speed distribution.

3.3.3.1 *Analysis techniques*

A before and after analysis approach was used to test hypothesis 3. June, July, and August of 2002 were the three full "during" months when the 55 mph speed limit was in effect. To rule out the seasonal effect, the same three months in 2001 and 2003 were selected as the before and after periods, respectively. The average speed daily profiles were aggregated using data from the three months before, during, and after periods for the selected freeway sections. The AADT data were obtained for the same selected sections to represent the travel growth. Average speeds of the before, during, and after periods were compared. The trend of the average speeds for the three periods was compared with the trend of AADT for the same periods.

The assumption made on the relationship of the average speed and AADT is that the higher AADT would cause the lower average speed during the peak period. Therefore, the average speed and AADT would be expected to have exactly opposite trend of the before, during, and after periods. If the expected trend of average speed was discontinued for the "during" period, the speed limit may be considered as the cause for the interruption of the trend.

3.3.3.2 *Confounding factors*

The approach to test hypothesis 3 can also be described as a before and after quasi-experimental design. The reason that the approach is not an experimental design is because the researchers could not control the population group, location, timing, or manner in which the speed limit was lowered. The before and after quasi-experimental design has one major limitation, namely, rival events such as car accidents. Rival events occurring at the same times as speed limit change are the most serious threat to the internal validity of the study findings. These rival events could be responsible for any observed change in travel time distribution. Rival events could also provide potential alternative explanations for these findings. This problem can be overcome when the likelihood of rival events can be discounted.

The considered rival events for this time series quasi-experiment were 1) an abnormal increase of accidents in the three-month period of 2002, which might be the cause of the longer travel time, 2) severe weather events in the three-month period of 2002, which might cause changes in speed or travel time distribution, and 3) work zones that occurred during the three-month period of 2002. These confounding factors were examined for their effects on travel time distribution change before any conclusion is drawn on the effect of speed limit changes.

3.3.3.3 *Analysis scenarios*

Both off-peak, peak periods and peak hour are examined for the effect of speed limit change on travel time distribution.

3.3.3.4 *Statistical analysis*

The Analysis of Variance (ANOVA) tests were used to compare the difference of the average speeds of the before, during, and after analysis periods. The Tukey's

Studentized Range tests were further performed to compare the average speeds between each pair of the three analysis periods. The performed ANOVA tests were:

- Test 1: The Analysis of Variance on the average speeds for the off peak period
- Test 2: The Analysis of Variance on the average speeds for the peak period
- Test 3: The Analysis of Variance on the average speeds for the peak hour

The null test of ANOVA for hypothesis 3 (speed limit has no effect on travel time distribution) can be illustrated by Equation 3.11:

$$H_{03:}\, S_B = S_D = S_A \qquad \text{Equation 3.11}$$

where:

S_B = the average speed of the before analysis period;

S_D = the average speed of the during analysis period; and

S_A = the average speed of the after analysis period;

The null test of Tukey's Studentized Range for hypothesis 3 (average speeds of any two of the three analysis periods are equal) can be illustrated by Equation 3.12:

$$H_{03a:}\, S_B = S_D \text{ or } S_B = S_A \text{ or } S_D = S_A \qquad \text{Equation 3.12}$$

where:

S_B = the average speed of the before analysis period;

S_D = the average speed of the during analysis period; and

S_A = the average speed of the after analysis period;

CHAPTER IV
RESEARCH PROCEDURES

This chapter presents the detailed procedures involved in testing the three research hypotheses. First, the chapter introduces the data source and the study sites as well as their selection criteria for the research; then the chapter describes the process of data aggregation and quality control; and finally, the final datasets for each hypothesis testing are presented.

4.1 Source of Data

The archived traffic data from the Mobility Monitoring Program (MMP) were used for this research. The MMP is a data collection effort by the Federal Highway Administration (FHWA) to track and report traffic congestion and travel reliability using archived ITS data from many metropolitan regions. The MMP started in 2001, and by the end of the 2004 covered a total of 29 cities and 3,000 freeway miles (*5*).

Traffic operations center archives are the data archives that store continuously collected data from field sensors. Due to complexities in data formats and storage, it has been difficult to use this data archive approach to incorporate real time intelligent transportation system (ITS) data until recently. All MMP data except one city (Houston) were collected by point sensors that collect data at point locations. A variety of point sensor technologies including single and double inductance loops, microwave radar, passive acoustic, and video image processing are used in the data collection. All of these technologies use a small, fixed zone of detection. Traffic measurements such as speed and volume were taken when a vehicle passed through this detection zone. These sensors are typically located at half-mile to one-mile intervals in every lane. For Houston, travel time data is collected by a toll tag identification system or automatic vehicle identification (AVI) system. The advantage of the AVI system compared to point sensors is that travel time is directly collected by the AVI sensors while point sensors collect spot speeds which are then aggregated over a distance to estimate the travel time. On the other hand, the advantage of point sensors is that it collects both spot speed and volume data. The AVI system only collects travel time with no volume data.

In MMP, the real-time data are sent from a field computer to a central database (typically a traffic center) at 20-second to 2-minute intervals to transfer and store the data. Internal processes at the traffic center aggregate the traffic data to specific time intervals for archival purposes. These time intervals vary from 20 seconds (basically no aggregation) to 15 minutes. The aggregated data are then stored in text files or data bases unique to each traffic center. The MMP processes these detector data sent from those participating cities, performs data quality checking, and standardizes these datasets for mobility estimation.

The standardized dataset for point sensors has the level of detail of 5-minute lane-by-lane traffic volume, speed, and in some cities, the occupancy data. The standardized dataset for the Houston toll tag system is 5-minute space mean speed between adjacent toll tag reader sites. The standardized datasets of 2006 from MMP are used for this research.

4.2 Study Sites

Because it is important to evaluate the impacts of a congestion threshold on a system-wide basis and not simply on a single road segment or a road segment in a single urban area, study sites were selected to cover all identified influential factors and the range of their values.

4.2.1 Study Sites for Hypothesis 1

Freeway segments were selected from seven urban areas to represent a variety of traffic and land use patterns. These seven urban areas are Chicago, Houston, Los Angeles, Minneapolis-St. Paul, Philadelphia, San Francisco, and Tampa. The selection of the cities was based on:

- availability of the data from MMP,

- geographic coverage, and
- metropolitan population.

Los Angeles and Chicago metropolitan areas had a population of over 7 million in 2006. Houston, San Francisco and Philadelphia metropolitan area had a population between 3 and 7 million. Minneapolis-St. Paul and Tampa had a population of less than 3 million. No urban areas with population below 1 million are available in the MMP.

Freeway sections were selected from these seven urban areas. The basic consideration in selecting freeway sections is homogeneity of the section. Combining sections with different characteristics into analysis units would mix the effects and jeopardize the findings because the sections were not homogenous. The detailed selection criteria are explained as follows.

- Consistent number of lanes within the section. The consistent number of lanes will ensure relatively homogeneity in terms of capacity of the freeway section. It should be noted that the detailed geometry of the segments such as existence of shoulders or horizontal and vertical profile (both of which affect capacity of the road) are not available for this research. However, since all sections are freeways, the design criteria for freeways are fairly consistent under different terrains and land uses; the difference in capacity caused by detailed geometry is assumed to be small.
- Length between 2 and 10 miles. This length should be able to represent a through traffic pattern and a short, but representative trip for the freeway. Section lengths shorter than 2 miles may not be long enough to capture the travel pattern. However, lengths longer than 10 miles may mix traffic patterns and road characteristics of two different sections. It should be noted that the length for a few sections were less than 2 miles in this research. The reason is that in certain cities the full range of freeway capacity cannot be covered. For example, in Los Angeles, two-lane freeways in one direction are almost non-existent. In order to

sample the sections across all traffic and land use patterns, the section length criteria was compromised for a few situations.

- No major bottlenecks within the section, except at the beginning or end of the section. The traffic characteristics of the freeway segments before and after a major bottleneck are often different due to the turning movements and capacity of the interchanges.
- Sensor consistency throughout the analysis period. The criterion ensures that the field sensor placement is stable throughout the analysis period and no new sensors were added in the segments during the analysis period. It was found from the previous research (*16*) that sensor spacing of a segment would affect the performance measures calculated for the segment. Therefore, sensor consistency would mean that any differences in the traffic measurements were due to changes in the operating conditions.

Approximately 20 sites from most urban areas except Houston were selected for the analysis. Since Houston is the only area that has the AVI toll tag data, the sample size were doubled for the reason of statistical significance. A total of 149 sites were selected for the analysis. The number of freeway segments at different capacity levels for each urban area, however, is not equal. Those more populated urban areas tend to have more high-capacity freeway facilities, such as 4-lane and above freeways. On the other hand, the less populated urban areas tend to have more low-capacity freeway facilities, such as 2 or 3-lane freeways. The number of segments selected for each urban area reflects this real-world condition.

Tables 4.1 and 4.2 summarize the urban areas and the study sites for each urban area, respectively. Figures 4.1 through 4.7 show the locations of sections on the map of the seven urban areas.

TABLE 4.1 Freeway Sections Summary

Urban area	Number of directional study sections for each lane configuration					Directional mileage for each lane configuration				
	2	3	4	5+	Total	2	3	4	5+	Total
Chicago	4	8	4	2	18	10.04	35.22	21.61	2.08	68.95
Houston	2	21	5	11	39	12.00	101.80	18.40	31.10	163.3
Los Angeles	2	5	5	7	19	4.86	16.46	28.12	24.47	73.91
Minneapolis-St. Paul	6	10	2	1	19	29.16	34.50	5.71	2.90	72.27
Philadelphia	10	8	5	0	23	53.14	38.59	28.52	0	120.25
San Francisco	5	4	5	4	18	34.24	22.78	26.85	10.09	93.95
Tampa	4	6	2	1	13	24.83	36.77	12.28	2.66	76.54
Total	33	62	28	26	149	168.27	286.12	141.49	73.3	669.17

TABLE 4.2 Freeway Study Sections

Number	Urban area	Section ID	Route	Direction	Beginning Route	Ending Route	Length (miles)
1	Chicago	CHI2A	I-190	WB	SB US-45	WB I-190	2.01
2	Chicago	CHI2B	Elgin O'Hare Expressway	EB	IRVING PARK	MEACHAM	4.37
3	Chicago	CHI2C	I-94	EB	NB SOUTH COTTAGE GROVE AVE	EB EAST 103RD ST	1.16
4	Chicago	CHI2D	I-90	WB	NB SOUTH STATE ST	WB WEST 51ST ST	2.50
5	Chicago	CHI3A	I-290	EB	NB NORTH MILL RD	SB NORTH CHURCH RD	3.91
6	Chicago	CHI3B	I-290	EB	NB EMROY AVE	SB I-294	2.83
7	Chicago	CHI3C	I-55	NB	SB SOUTH NAPERVILLE RD	SB MURPHY RD	4.27
8	Chicago	CHI3D	I-55	SB	NB WOLF RD	NB LEMONT RD	7.08
9	Chicago	CHI3E	I-57	NB	WB 175TH ST	NB KEDZIE AVE	4.07
10	Chicago	CHI3F	I-80	EB	SB I-94	SB WENTWORTH AVE	2.82
11	Chicago	CHI3G	I-90	EB	NB NORTH CUMBERLAND AVE	SB EDENS EAST EXPY	5.27
12	Chicago	CHI3H	SR-53	SB	EB EAST DUNDEE RD	WB WEST KIRCHOFF RD	4.97
13	Chicago	CHI4A	I-290	WB	NB SOUTH CANAL ST	SB SOUTH CENTRAL AVE	6.77
14	Chicago	CHI4B	I-90	EB	SB NORTH PULASKI RD	WB NORTH MILWAUKEE AVE	5.62
15	Chicago	CHI4C	Lake Shore Drive (41)	NB	US-41	FIELD PLAZA	5.23
16	Chicago	CHI4D	I-290	EB	WB HIGGINS RD	EB WEST IRVING PARK RD	4.00
17	Chicago	CHI5A	I-90	EB	NB NORTH OGDEN AVE	WB WEST ADAMS ST	1.48
18	Chicago	CHI5B	I-90	WB	EB WEST MONROE ST	WB WEST RANDOLPH ST	0.60
19	Houston	HOU2A	Hardy Toll Road	SB	IH-45 North	FM-1960	6.00

TABLE 4.2 Continued

Number	Urban area	Section ID	Route	Direction	Beginning Route	Ending Route	Length (miles)
20	Houston	HOU2AO	Hardy Toll Road	NB	FM-1960	IH-45 North	6.00
21	Houston	HOU3A	US 290 Northwest	EB	Barker Cypress	FM 1960	4.05
22	Houston	HOU3AO	US 290 Northwest	WB	FM 1960	Barker Cypress	4.90
23	Houston	HOU3B	US 290 Northwest	EB	FM 1960	Sam Houston	5.10
24	Houston	HOU3BO	US 290 Northwest	WB	Sam Houston	FM 1960	4.25
25	Houston	HOU3C	US 290 Northwest	EB	Sam Houston	Pinemont	4.45
26	Houston	HOU3CO	US 290 Northwest	WB	Pinemont	Sam Houston	4.45
27	Houston	HOU3D	I-45 North	SB	Hardy Toll Road	FM 1960	5.40
28	Houston	HOU3DO	I-45 North	NB	FM 1960	Hardy Toll Road	5.40
29	Houston	HOU3E	Beltway 8-North	EB	US-290 Northwest	SH-249	6.00
30	Houston	HOU3EO	Beltway 8-North	WB	SH-249	US-290 Northwest	6.10
31	Houston	HOU3F	Beltway 8-North	EB	SH-249	Ella	5.50
32	Houston	HOU3FO	Beltway 8-North	WB	Ella	SH-249	5.50
33	Houston	HOU3G	Beltway 8-North	WB	John F Kennedy Blvd	Imperial Valley	4.70
34	Houston	HOU3H	Beltway 8-West	SB	I-10 Katy	Richmond	4.60
35	Houston	HOU3I	Beltway 8-West	SB	Richmond	US 59 Southwest	4.20
36	Houston	HOU3J	Hardy Toll Road	SB	FM-1960	Greens	5.80
37	Houston	HOU3JO	Hardy Toll Road	NB	Greens	FM-1960	5.80
38	Houston	HOU3K	Hardy Toll Road	SB	Aldine-Bender	Little York	4.20
39	Houston	HOU3KO	Hardy Toll Road	NB	Little York	Aldine-Bender	4.20
40	Houston	HOU3L	Hardy Toll Road	SB	Little York	IH-610 North Loop	3.60
41	Houston	HOU3LO	Hardy Toll Road	NB	IH-610 North Loop	Little York	3.60
42	Houston	HOU4A	US 59 Southwest	EB	Hazard	I-45	3.60
43	Houston	HOU4B	SH-288	NB	IH-610 South Loop	US 59	3.30
44	Houston	HOU4BO	SH-288	SB	US 59	IH-610 South Loop	3.30
45	Houston	HOU4C	I-45 North	SB	Aldine Bender	Shepherd	3.60
46	Houston	HOU4D	I-45 North	SB	Shepherd	Crosstimbers	4.60
47	Houston	HOU5A	US 59 Southwest	EB	Bissonnet	Hillcroft	5.10
48	Houston	HOU5B	US 59 Southwest	WB	Hillcroft	Bissonnet	5.10
49	Houston	HOU5C	I-610 East Loop	NB	SH 225	Clinton Dr	2.70

TABLE 4.2 Continued

Number	Urban area	Section ID	Route	Direction	Beginning Route	Ending Route	Length (miles)
50	Houston	HOU5D	I-610 East Loop	NB	Clinton Dr	Wallisville Rd	3.30
51	Houston	HOU5E	I-610 East Loop	SB	N Wayside	I-10 East	2.30
52	Houston	HOU5F	I-610 East Loop	SB	I-10 East	Clinton Dr	2.90
53	Houston	HOU6A	US 59 Southwest	EB	Hillcroft	I-610	1.60
54	Houston	HOU6B	US 59 Southwest	EB	Newcastle	Hazard	2.50
55	Houston	HOU6C	US 59 Southwest	WB	Hazard	Newcastle	2.50
56	Houston	HOU6D	US 59 Southwest	WB	I-610	Hillcroft	1.60
57	Houston	HOU6E	I-610 North Loop	EB	Irvington	US 59	1.50
58	Los Angeles	LAX2A	CA-118	EB	N Princeton Ave.	N. Madera Rd.	4.21
59	Los Angeles	LAX2B	I-105	WB	Studebaker Rd.	I-605	0.65
60	Los Angeles	LAX3A	CA-118	EB	N. Madera Rd.	Tapo Canyon Rd.	1.70
61	Los Angeles	LAX3B	I-105	EB	I-110	I-710	3.55
62	Los Angeles	LAX3C	I-5	NB	Valley View Ave.	I-605	3.58
63	Los Angeles	LAX3D	I-5	SB	I-605	Valley View Ave.	4.48
64	Los Angeles	LAX3E	CA-14	SB	Soledad Canyon Rd.	CA-126	3.16
65	Los Angeles	LAX4A	I-5	NB	I-605	I-710	5.00
66	Los Angeles	LAX4B	I-10	EB	I-710	CA-19	4.38
67	Los Angeles	LAX4C	CA-60	EB	S. Hacienda Blvd.	CA-57	7.18
68	Los Angeles	LAX4D	US-101	NB	CA-110	N. Western Ave.	4.97
69	Los Angeles	LAX4E	I-405	NB	I-110	I-105	6.61
70	Los Angeles	LAX5A	I-10	EB	N. Grand Ave.	CA-57	4.09
71	Los Angeles	LAX5B	CA-60	WB	I-605	Garfield Ave.	4.98
72	Los Angeles	LAX5C	I-210	WB	Rosemead Blvd.	CA-134	4.04
73	Los Angeles	LAX5D	I-405	NB	CA-2	US-101	7.15
74	Los Angeles	LAX6A	I-5	SB	CA-118	CA-170	1.73
75	Los Angeles	LAX6B	I-10	EB	I-5	I-710	1.47
76	Los Angeles	LAX6C	I-710	SB	I-105	Alondra Blvd.	1.03
77	Minneapolis-St. Paul	MSP2A	T.H.36	WB	Railroad Bridge	Cleveland Ave	4.89
78	Minneapolis-St. Paul	MSP2B	T.H.62	EB	Wooddale Ave	T.H.121	3.07
79	Minneapolis-St. Paul	MSP2C	U.S.169	NB	Bren Rd	22nd St	5.07

TABLE 4.2 Continued

Number	Urban area	Section ID	Route	Direction	Beginning Route	Ending Route	Length (miles)
80	Minneapolis-St. Paul	MSP2D	I-494	EB	67th Ave	T.H.55	4.99
81	Minneapolis-St. Paul	MSP2E	I-35E	NB	Southcross Dr	N of T.H.77	5.07
82	Minneapolis-St. Paul	MSP2F	T.H.10	EB	Ferry St	W of Egret	6.09
83	Minneapolis-St. Paul	MSP3A	T.H.77	NB	Old Shakopee Rd	N of Minnesota River	3.62
84	Minneapolis-St. Paul	MSP3B	T.H.100	NB	Benton Ave	Excelsior Blvd	2.81
85	Minneapolis-St. Paul	MSP3C	I-394	EB	I-494	Co Rd 73	2.26
86	Minneapolis-St. Paul	MSP3D	I-694	EB	T.H.47	5th Ave	3.77
87	Minneapolis-St. Paul	MSP3E	I-35W	NB	Co Rd C	I-694	3.49
88	Minneapolis-St. Paul	MSP3F	I-35E	NB	S of Cliff Rd	Pilot Knob Rd	4.22
89	Minneapolis-St. Paul	MSP3G	I-35E	NB	Cayuga St	T.H.36	3.77
90	Minneapolis-St. Paul	MSP3H	I-35W	SB	I-694	Co Rd C	3.50
91	Minneapolis-St. Paul	MSP3I	I-35E	SB	T.H.36	Cayuga St	3.77
92	Minneapolis-St. Paul	MSP3J	I-35W	NB	N of I-494	S of I-494	3.29
93	Minneapolis-St. Paul	MSP4A	I-94	EB	49th Ave	41st Ave	3.20
94	Minneapolis-St. Paul	MSP4B	I-35W	NB	42nd St	26th St	2.51
95	Minneapolis-St. Paul	MSP5A	I-94	WB	Olson Hwy	Plymouth Ave	2.90
96	Philadelphia	PHL2A	I-476	SB	US-1	I-95	5.39
97	Philadelphia	PHL2B	I-76	WB	US-1	I-476	3.30
98	Philadelphia	PHL2C	I-95	NB	I-276	US-1	6.25
99	Philadelphia	PHL2CO	I-95	SB	US-1	I-276	6.25
100	Philadelphia	PHL2D	I-95	NB	US-1	PA-29	4.30
101	Philadelphia	PHL2DO	I-95	SB	PA-29	US-1	4.30
102	Philadelphia	PHL2E	PA-309	NB	I-276	N. Bethlehem Pike	5.33
103	Philadelphia	PHL2EO	PA-309	SB	N. Bethlehem Pike	I-276	5.33
104	Philadelphia	PHL2F	US 202	NB	US-30	N. Valley Rd.	4.52
105	Philadelphia	PHL2G	US 422	WB	I-276	Collegeville Rd.	8.17
106	Philadelphia	PHL3A	I-476	NB	PA-3	I-76	6.52
107	Philadelphia	PHL3AO	I-476	SB	I-76	PA-3	6.52
108	Philadelphia	PHL3B	I-95	NB	Bartram Ave.	I-76	6.34
109	Philadelphia	PHL3C	I-95	NB	PA-73	PA-132	4.40

TABLE 4.2 Continued

Number	Urban area	Section ID	Route	Direction	Beginning Route	Ending Route	Length (miles)
110	Philadelphia	PHL3D	I-95	SB	I-476	I-495	7.10
111	Philadelphia	PHL3E	I-76	EB	US-1	I-676	1.99
112	Philadelphia	PHL3F	I-76	WB	I-676	US-1	1.98
113	Philadelphia	PHL3G	US 202	NB	N. Valley Rd.	US-422	3.75
114	Philadelphia	PHL4A	I-95	NB	I-476	Bartram Ave.	4.78
115	Philadelphia	PHL4AO	I-95	SB	Bartram Ave.	I-476	4.78
116	Philadelphia	PHL4B	I-95	NB	PA-90	PA-73	7.75
117	Philadelphia	PHL4BO	I-95	SB	PA-73	PA-90	8.65
118	Philadelphia	PHL4C	I-76	WB	I-95	Snyder Ave.	2.56
119	San Francisco	SAF2A	SR-92	EB	I-280	I-380	7.14
120	San Francisco	SAF2B	SR-92	WB	I-380	I-280	4.83
121	San Francisco	SAF2C	I-680	SB	Gold Hill Rd.	I-780	8.89
122	San Francisco	SAF2D	SR-87	NB	SR-85	I-280	4.53
123	San Francisco	SAF2E	I-680	NB	I-780	Gold Hill Rd.	8.87
124	San Francisco	SAF3A	I-80	EB	SR-4	Port St.	5.38
125	San Francisco	SAF3B	I-84	WB	Thornton Ave.	US-101	7.93
126	San Francisco	SAF3C	SR-237	WB	I-880	US-101	4.73
127	San Francisco	SAF3D	I-880	SB	US-101	I-280	4.75
128	San Francisco	SAF4A	I-80	EB	Buchanan St.	San Pablo Dam Rd.	3.89
129	San Francisco	SAF4B	580	EB	SR-24	SR-13	6.75
130	San Francisco	SAF4C	I-680	SB	SR-24	Sycamore Valley Rd.	4.63
131	San Francisco	SAF4D	I-880	SB	SR-84	SR-262	6.24
132	San Francisco	SAF4E	I-880	SB	29th Ave.	I-238	5.33
133	San Francisco	SAF5A	I-80	EB	I-880	Buchanan St.	2.81
134	San Francisco	SAF5B	I-880	NB	SR-92	I-238	3.17
135	San Francisco	SAF5C	I-880	SB	I-238	SR-92	3.19
136	San Francisco	SAF6A	I-680	SB	Oak Park Blvd.	SR-24	0.93
137	Tampa	TAM2A	I-275	NB	US-41	I-75	5.85
138	Tampa	TAM2AO	I-275	SB	I-75	US-41	5.85
139	Tampa	TAM2B	I-75	NB	US-301	I-275	5.91

TABLE 4.2 Continued

Number	Urban area	Section ID	Route	Direction	Beginning Route	Ending Route	Length (miles)
140	Tampa	TAM2BE	I-75	SB	I-275	US-301	7.22
141	Tampa	TAM3A	I-275	NB	I-4	US-41	7.20
142	Tampa	TAM3B	I-4	EB	I-75	SR-39	7.52
143	Tampa	TAM3BO	I-4	WB	SR-39	I-75	7.52
144	Tampa	TAM3C	I-75	NB	I-4	US-301	6.60
145	Tampa	TAM3CE	I-75	SB	US-301	I-4	4.05
146	Tampa	TAM3D	I-75	SB	I-4	SR-60	3.88
147	Tampa	TAM4A	I-275	NB	SR-687	SR-60	6.77
148	Tampa	TAM4B	I-275	SB	SR-60	US-92	5.51
149	Tampa	TAM5A	I-275	NB	SR-694	SR-687	2.66

FIGURE 4.1 Chicago area study sites.

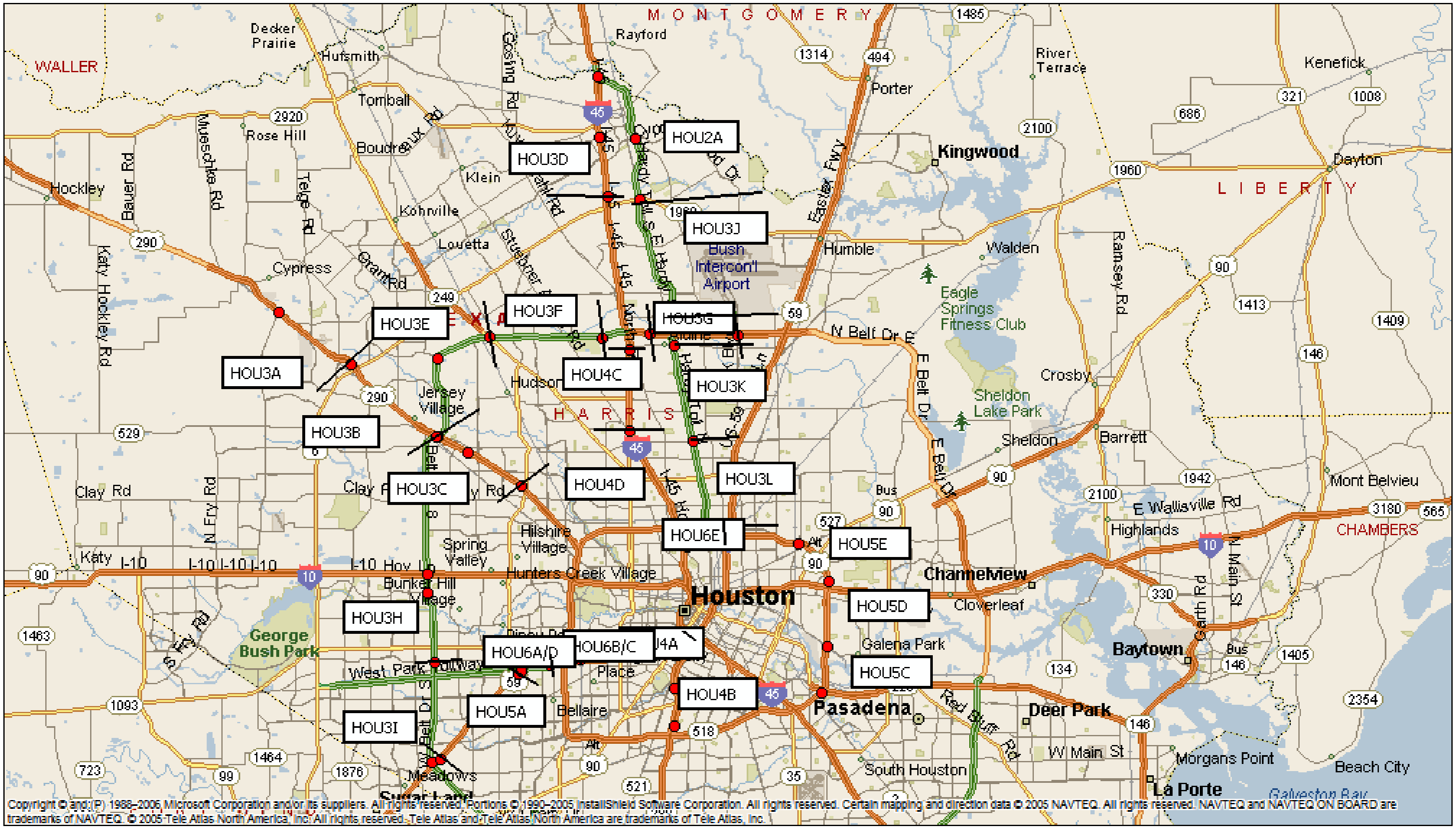


FIGURE 4.2 Houston area study sites.

FIGURE 4.3 Los Angeles area study sites.

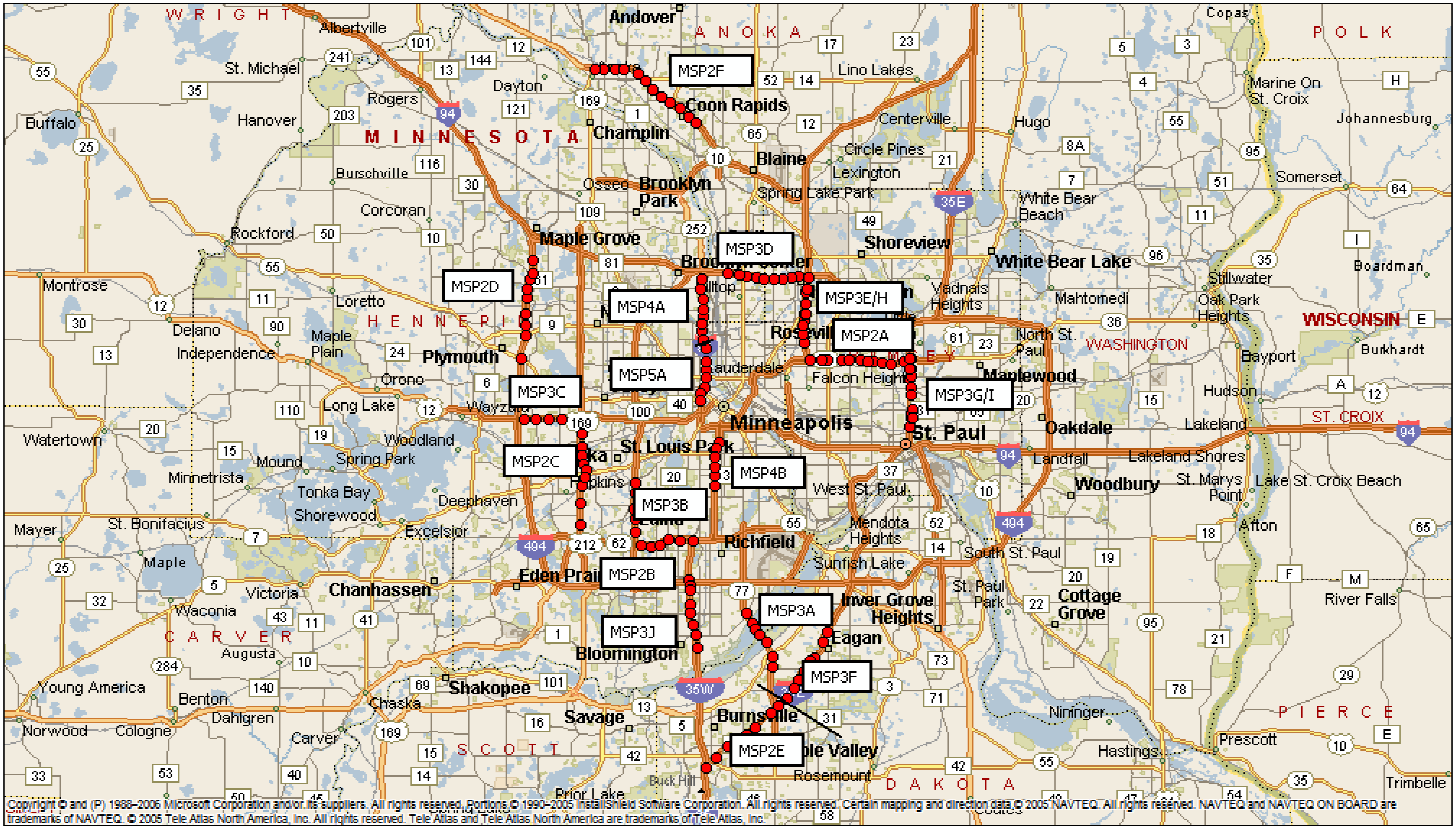


FIGURE 4.4 Minneapolis-St. Paul area study sites.

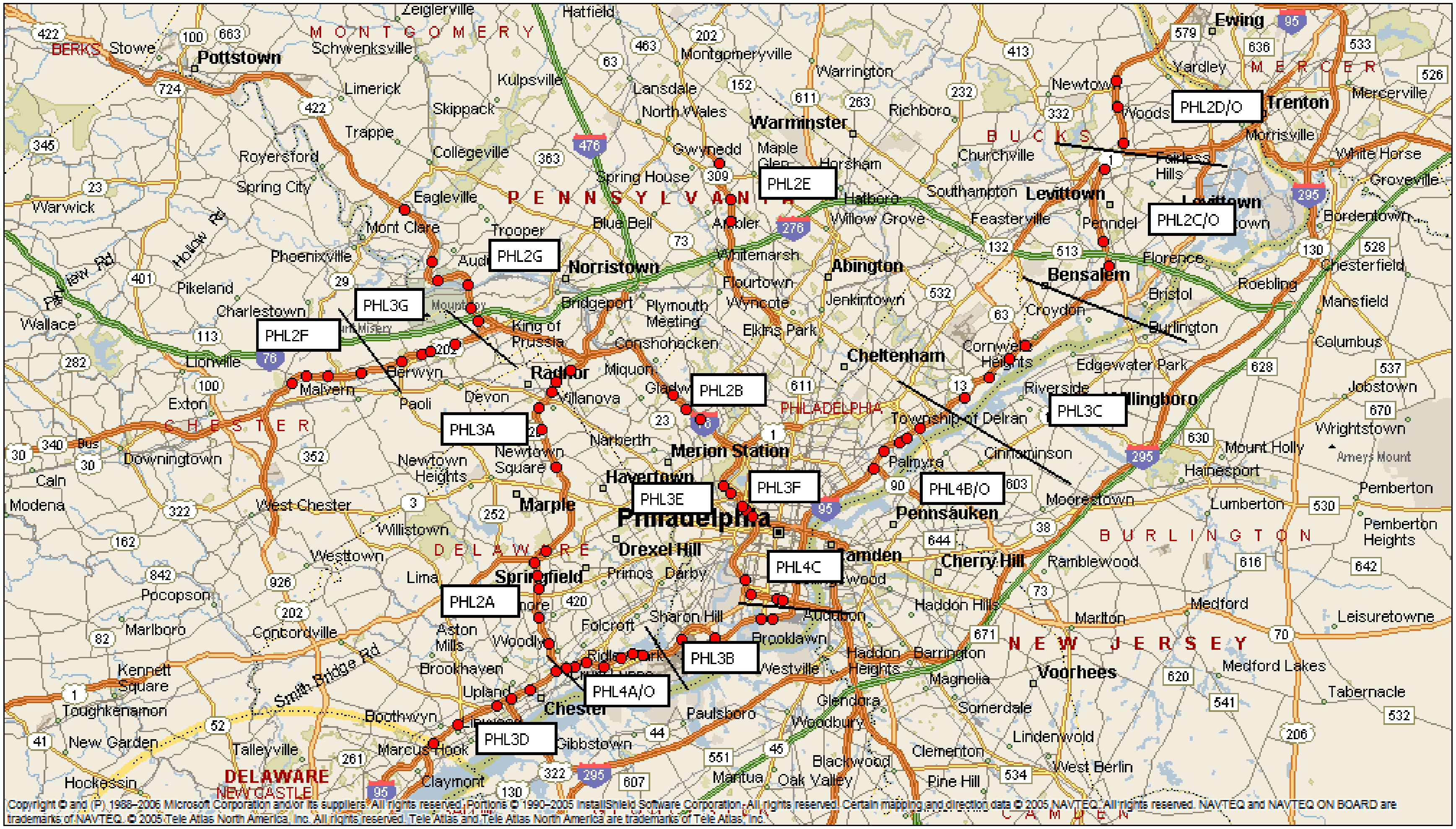


FIGURE 4.5 Philadelphia area study sites.

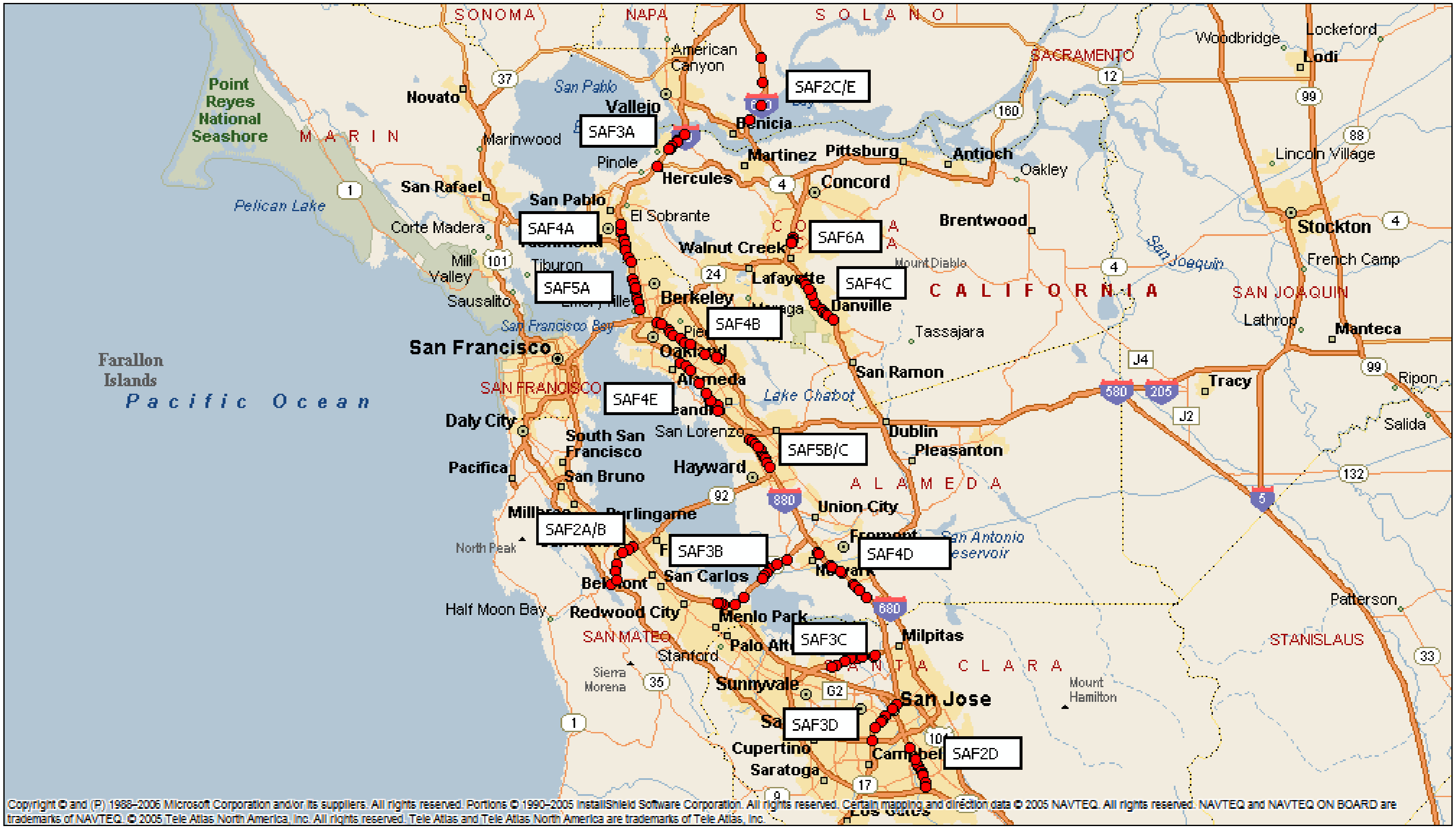


FIGURE 4.6 San Francisco area study sites.

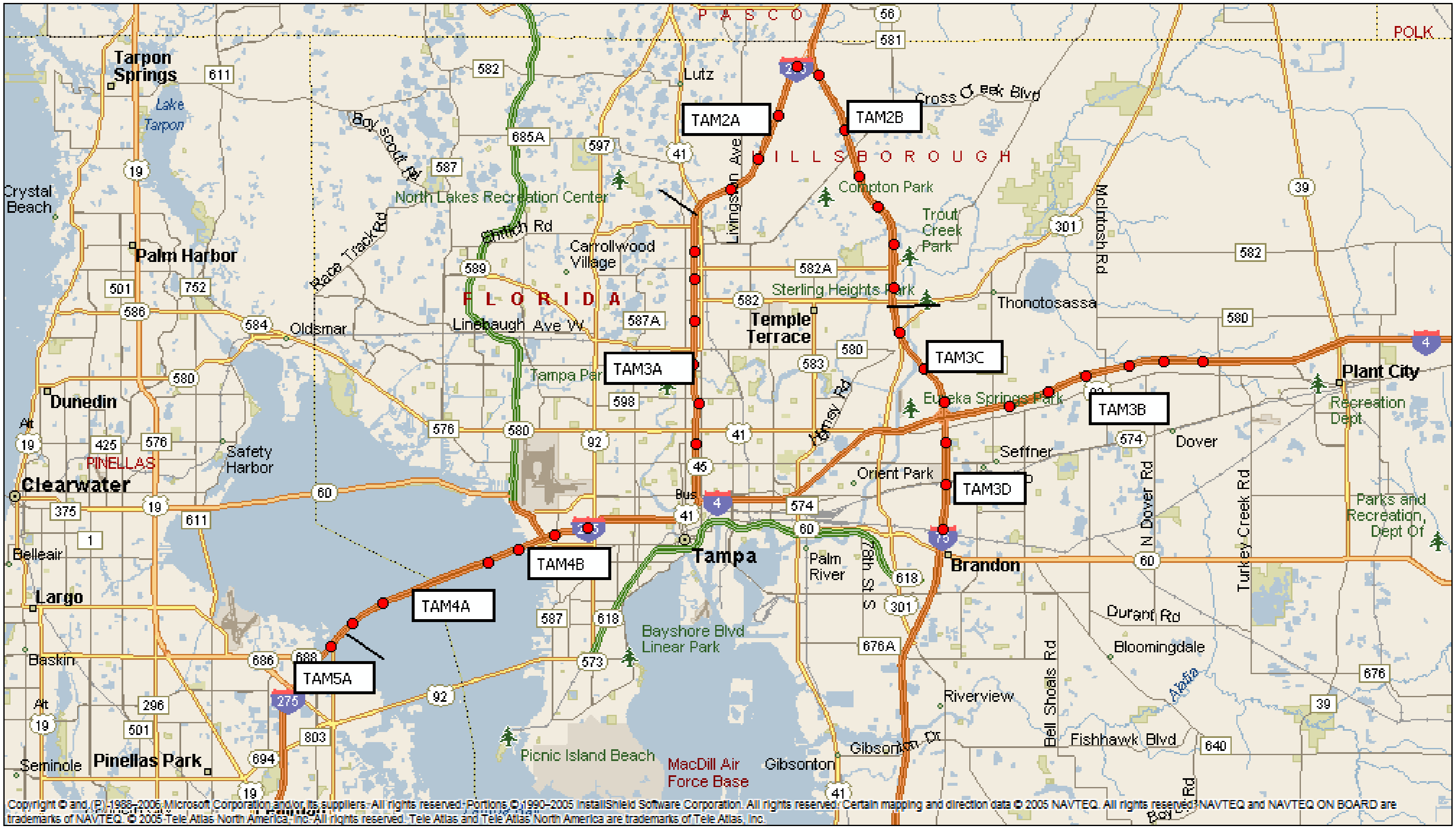


FIGURE 4.7 Tampa area study sites.

Table 4.3 lists the number of the study sites in each range of factors considered in this study. As mentioned, the data from MMP were originally collected for traffic operations purposes. Thus, the coverage of the data is limited to those places where real-time traffic data are collected and archived. No sites in rural area type are available. Since congestion tends to occur in larger urban areas, the lack of rural and less populated urban area data is believed to have little or no effect on the study findings.

The data source for the factors of AADT, percentage of truck, and speed limit is the Highway Performance Monitoring System (HPMS) which is a program designed to assess the condition performance of the nation's highways annually. It should be noted that 8 of 149 freeway sections do not have data available in HPMS (7 of them are toll ways). There are additional 15 freeway sections that do not have the percent trucks and the speed limit data available in HPMS. The lack of the data for this small number of sections is believed to have a small influence on the overall study findings. Because the purpose of considering these factors is to ensure that the experiment performed cover a variety of factors and conditions.

4.2.2 Study Sites for Hypothesis 2

The analysis of hypothesis 2 requires the study sites from system wide as does hypothesis 1. The consideration and selection criteria for study sites of hypotheses 2 are the same. Therefore, the study sites for hypothesis 1 can also be used for hypothesis 2.

4.2.3 Study Sites for Hypothesis 3

One of the concerns in selecting study sites for testing hypothesis 3 is that the inconsistency in law enforcement efforts may influence driving behaviors, which in turn, influence the travel time distribution of freeway segments. Harris County covers the majority of the urban area in the Houston metropolitan area. Freeway and toll way law enforcement in the county is geographically divided into four Precincts. To ensure the consistency in law enforcement effort, freeway segments located in Precinct 3 were selected for testing hypotheses 3. Precinct 3 has the most regular shape for the coverage area. The regular shape of the coverage area would likely to incorporate freeway sections completely within the precinct as well as to have a similar number of patrols for each freeway route, and in turn, increase the chance of consistency in law enforcement effort.

The freeway segments for hypothesis 3 are listed in Table 4.4 and shown in Figure 4.8.

TABLE 4.3 Number of Freeway Sections Sampled in Factor Groups

Factors	Levels	Area Type			
		CBD	Urban	Suburban	Rural
Area Size	Small (less than 500,000 population)	-	-	-	-
	Medium (500,000 – 1 million population)	-	-	-	-
	Large (1 – 3 million population)	1	13	18	-
	Very Large (3 - 7 million population)	6	33	41	-
	Very Large (over 7 million population)	6	11	20	-
Congestion Level	Low (AADT/C <7)	3	9	13	-
	Moderate (AADT/C 7-11)	3	22	26	-
	Severe (AADT/C >11)	7	26	32	-
Number of Lanes Per Direction	2	0	10	23	-
	3	2	18	42	-
	4	7	16	5	-
	5+	4	13	9	-
Percent Trucks	<10%	10	46	50	-
	>=10%	0	7	13	-
Proximity to Major Bottleneck	< 1 mile downstream from segment	11	32	26	-
	>1 miles downstream from segment	2	25	53	-
Ramp Spacing	<1 mile	1	5	13	-
	>1 mile	12	52	66	-
Speed Limit	50 mph	3	0	0	-
	55 mph	5	24	26	-
	60 mph	1	15	0	-
	65 mph	1	14	31	-
	70 mph	0	0	6	-

TABLE 4.4 Study Sites for Hypothesis 3

Sections	Route	Direction	Beginning Route	Ending Route	Length (miles)
1	I-10 Katy	EB	Barker Cypress	Sam Houston	7.60
2	I-10 Katy	WB	Sam Houston	Barker Cypress	7.40
3	I-10 Katy	EB	Sam Houston	I-610	6.30
4	I-10 Katy	WB	I-610	Sam Houston	6.55
5	US 59 Southwest	EB	Wilcrest	I-610	8.31
6	US 59 Southwest	WB	I-610	Wilcrest	8.31
7	Sam Houston Tollway	NB	Beechnut	Memorial Dr	6.20
8	Sam Houston Tollway	NB	Memorial Dr	US 290	8.80
9	Sam Houston Tollway	SB	US 290	I-10 Katy	7.20
10	Sam Houston Tollway	SB	I-10 Katy	US 59 Southwest	8.80

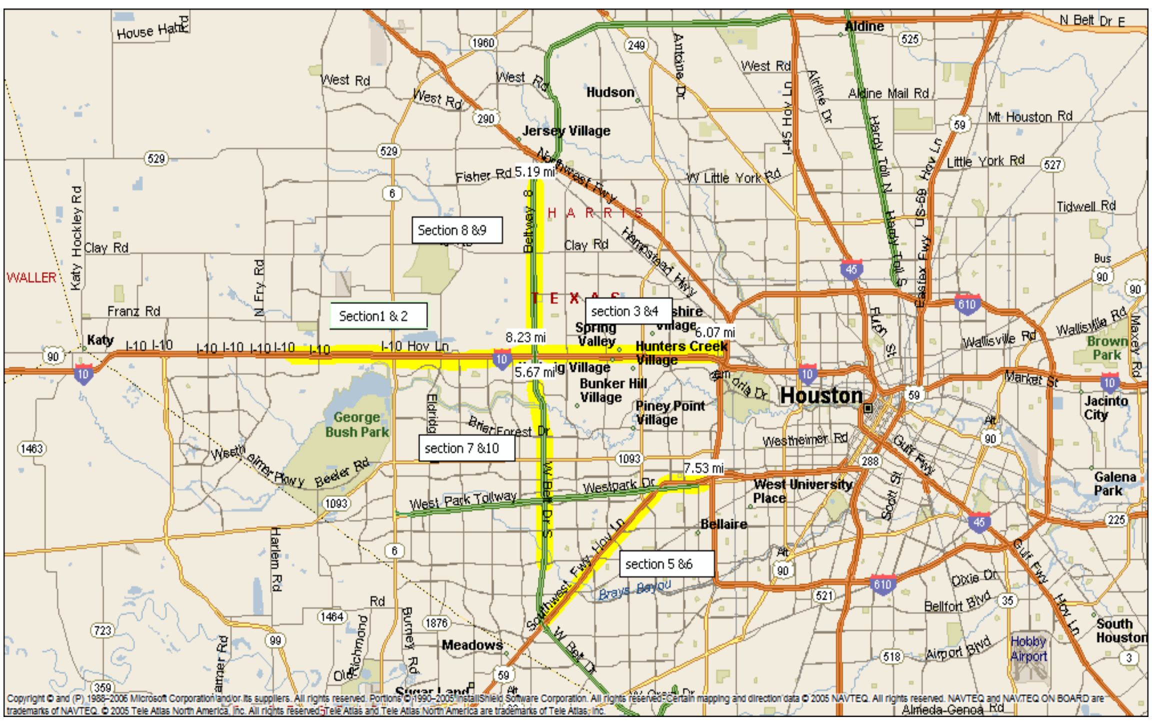


FIGURE 4.8 Locations of study sites for hypothesis 3.

4.3 Data Processing

The standardized datasets from MMP have the level of detail of 5-minute speed and volume data for each lane. These data were aggregated both spatially and temporally for each hypothesis testing.

4.3.1 Data Aggregation for Hypothesis 1

Six out of seven urban areas selected for the hypothesis 1 testing have point sensor data; Houston has toll tag data. The data aggregation process for point sensor data and toll tag data, however, is similar. The only difference is that toll tag data requires little or no spatial aggregation. The snap shot method (*16*) was used to transform spot speeds to travel time for the point sensors. The following sections detail the aggregation process.

4.3.1.1 *Spatial aggregation for point sensors*

Figure 4.9 illustrates four levels of aggregated point sensor data: lane-by-lane level, station level, link level, and section level (*5*). Three steps of spatial aggregation were performed on the standardized 5-minute lane by lane data to obtain section level of information. For each step, three parts of calculation were performed. The “sensor” data aggregation part describes the procedures for aggregating the volume and speed data. The “performance measures calculation” part introduces the calculation of performance measures (i.e., delay, TTI, and PTI) using the adjusted volume and speed data. The “adjustment for missing value” part explains the assumptions and procedures used to adjust the missing sensor data and resulting performance measures.

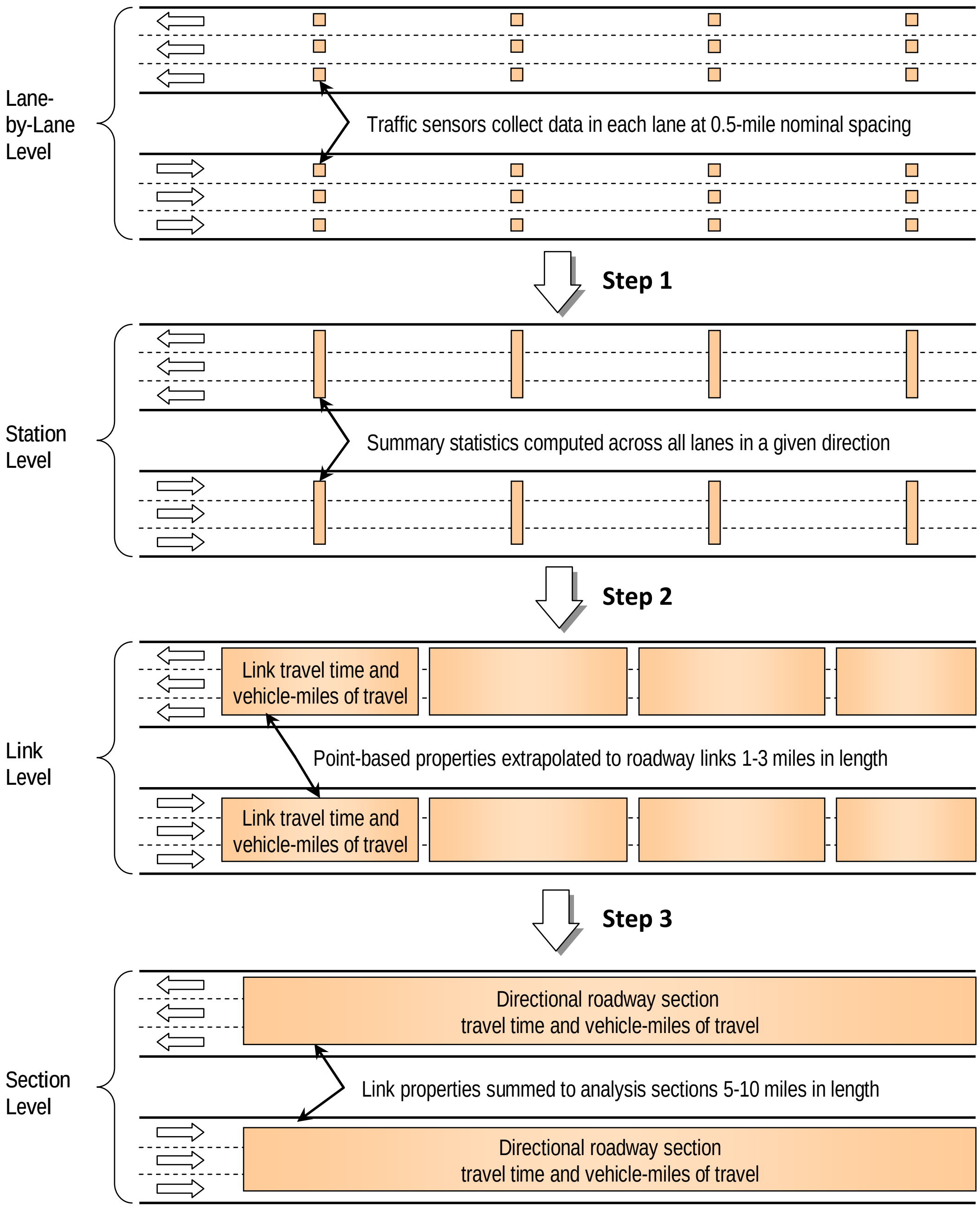


FIGURE 4.9 Illustration of spatial aggregation steps for point sensors (*5*).

1. Step 1

This step aggregates data laterally over all lanes in a direction. Both volume and speed data by lane for each 5-minute time slice were aggregated as if volume and speed data were from one sensor for all lanes in that direction.

- *Sensor Data Aggregation*

  Volume data were summed across all lanes for the station level volume as shown in Equations 4.1. The speed value for the station was obtained by weighing the speed per lane with the volume on the specific lane as the weighting factor. The speed aggregation procedure is shown in Equations 4.2.

$$v_i(t) = \sum_{j=1}^{n} v_j\,(t) \qquad \text{Equation 4.1}$$

where:

$v_i(t)$	=	Volume at time slice t for station i (vehicles);
$v_j(t)$	=	Volume at time slice t for lane j (vehicles);
n	=	Total number of lanes at station i;
t	=	5-minute time slice, one of 288 in each day;
j	=	Lane j in station i; and
i	=	Station i.

$$S_i(t) = \frac{\sum_{j=1}^{n} s_j(t) * v_j(t)}{\sum_{j=1}^{n} v_j(t)} \qquad \text{Equation 4.2}$$

where:

$S_i(t)$	=	Speed at time slice t for station i (mph);
$S_j(t)$	=	Speed at time slice t for lane j (mph);
$v_j(t)$	=	Volume at time slice t for lane j (vehicles);
n	=	Total number of lanes at station i;
t	=	5-minute time slice, one of 288 in each day;
j	=	Lane j in station i; and

i = Station i.

- *Performance Measure Calculation*

  No performance measure was calculated at this level.

- *Adjustment for Missing Value*

  Factoring is used as a way to estimate the missing volume and speed data from particular lane(s). The missing data are occasions when either no data is reported for a particular detector or the original data was discarded because it has been determined to be bad in the MMP data quality control process(*5*). The factoring ensures the consistency of data, especially when comparing among study sites. The assumptions made when estimating missing data are 1) volume is proportional to the ratio of missing number of lanes to the total number of lanes, and 2) speed is the same as the average speed of non-missing lanes.

  The station level data will be set to missing or null if data is missing from all lanes.

2. Step 2

This step expands the station level data to cover a small road link which has the detector station in the middle. The assumption for this step is that speed and volume is consistent or homogenous within the small link.

- *Sensor Data Aggregation*

  Figure 4.10 illustrates the distance covered by each detector station in a road section with four detector stations. For example, the second detector station covers a link that begins halfway between station 1 and station 2 and ends at half the distance to the downstream detector station 3. Each detector station covers a link beginning halfway from the detector station upstream ending halfway to the detector station downstream. The distance upstream of the first station on any road and downstream of the last station on a road is assumed to be the same as the distance from the station to its "interior" neighbor.

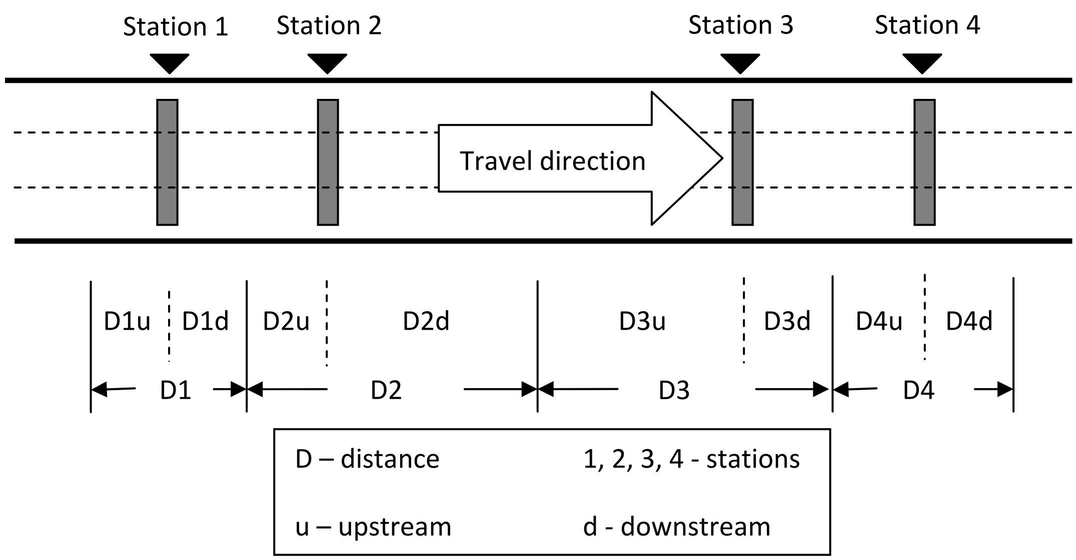


FIGURE 4.10 Illustration of distance coverage by detector stations.

Under the assumption that the speed and volume are homogenous within the link, the aggregated volume and speed values for the station become the volume and speed values of the link which has the coverage distance illustrated in Figure 4.10.

The link level VMT is the product of the volume of the link and the distance of the link (as shown in Equation 4.3). The link level travel time was calculated by dividing the distance of the link with the speed of the link (as shown in Equation 4.4). The link level VHT is the product of the volume of the link and the travel time of the link (as shown in Equation 4.5).

$$V_i(t) = v_i(t) * D_i \qquad \text{Equation 4.3}$$

where:

$V_i(t)$ = Vehicle Miles Traveled (VMT) at time slice t for link i (vehicle-mile);

$v_i(t)$ = Volume at time slice t for link i (vehicles);

D_i = Distance covered by link i (mile);

t = 5-minute time slice, one of 288 in each day; and

i = Link i.

$$T_i(t) = \frac{D_i}{S_i(t)} \qquad \text{Equation 4.4}$$

where:

$T_i(t)$ = Travel time at time slice t for link i (hour);

D_i = Distance covered by link i (mile);

$S_i(t)$ = Speed at time slice t for link i (mph);

t = 5-minute time slice, one of 288 in each day; and

i = Link i.

$$H_i(t) = v_i(t) * T_i(t) \qquad \text{Equation 4.5}$$

where:

$H_i(t)$ = Vehicle Hours Traveled (VHT) at time slice t for link i (vehicle hour);

$v_i(t)$ = Volume at time slice t for station i (vehicles);

$T_i(t)$ = Travel time at time slice t for link i (hour);

t = 5-minute time slice, one of 288 in each day; and

i = Link i.

- *Performance Measure Calculation*

  The performance measures delay and TTI were calculated for each link. The original equations for calculating delay and TTI can be seen in section 3.3.1.2. The equations can be reformulated with the symbols of the station link (as shown in Equations 4.6 and 4.7). The delay and TTI values were calculated for the eight congestion threshold scenarios introduced in section 3.3.1.3. Since only one measure of TTI is available at the 5-minute level and PTI is the 95th percentile of TTI, PTI cannot be calculated at this level.

$$Delay_i(t) = \left(\frac{1}{S_i(t)} - \frac{1}{congestion\ threshold\ speed}\right) \times V_i(t) \qquad \text{Equation 4.6}$$

where:

$Delay_i(t)$	=	Delay at time slice t for link i (vehicle hour);
$S_i(t)$	=	Speed at time slice t for link i (mph);
$V_i(t)$	=	VMT at time slice t for link i (vehicle-mile);
t	=	5-minute time slice, one of 288 in each day; and
i	=	Link i.

$$TTI_i(t) = \frac{congestion\ threshold\ speed}{S_i(t)} \qquad \text{Equation 4.7}$$

where:

$TTI_i(t)$	=	TTI at time slice t for link i.
$S_i(t)$	=	Speed at time slice t for link i (mph);
t	=	5-minute time slice, one of 288 in each day; and
i	=	Link i.

- *Adjustment for Missing Value*

  No adjustment of missing value for volume and speed data was performed at this step since the adjustment was already performed at the station level of Step 1.

3. Step 3

This step aggregates data for all links into a study section dataset.

- *Sensor Data Aggregation*

The section level VMT and VHT were obtained by summing the VMT and VHT of each link in the section (as shown in Equations 4.8 and 4.9). The space mean speed for the section can be estimated by dividing total section VMT by total section VHT. The Equation 4.10 illustrates the space mean speed aggregation procedure.

$$V_k(t) = \sum_{i=1}^{m} V_i(t) \qquad \text{Equation 4.8}$$

where:

$V_k(t)$ = VMT at time slice t for section k (vehicle mile);
$V_i(t)$ = VMT at time slice t for link i (vehicle-mile);
t = 5-minute time slice, one of 288 in each day;
m = Total number of links in section k; and
k = Section k.

$$H_k(t) = \sum_{i=1}^{m} H_i(t) \qquad \text{Equation 4.9}$$

where:

$H_k(t)$ = VHT at time slice t for section k (vehicle hour);
$H_i(t)$ = VHT at time slice t for link i (vehicle hour); and
t = 5-minute time slice, one of 288 in each day;
m = Total number of links in section k; and
k = Section k.

$$S_k(t) = \frac{V_k(t)}{H_k(t)} \qquad \text{Equation 4.10}$$

where:

$S_k(t)$ = Space mean speed at time slice t for section k (mph); and
$V_k(t)$ = VMT at time slice t for section k (vehicle mile);
$H_k(t)$ = VHT at time slice t for section k (vehicle hour);
t = 5-minute time slice, one of 288 in each day;
m = Total number of links in section k; and
k = Section k.

- *Performance Measure Aggregation*

  Performance measures calculated at the link level were aggregated to obtain section level performance measures. Section level delay was obtained by summing delay for all links in the section (as shown in Equation 4.11). Section level TTI was obtained by weighing the link level TTI with the link VMT as the weighting factor (as shown in Equation 4.12).

$$Delay_k(t) = \sum_{i=1}^{m} Delay_i\,(t) \qquad \text{Equation 4.11}$$

where:

$Delay_k(t)$	=	Delay at time slice t for section k (vehicle hour);
$Delay_i(t)$	=	Delay at time slice t for link i (vehicle hour);
t	=	5-minute time slice, one of 288 in each day;
m	=	Total number of links in section k; and
k	=	Section k.

$$TTI_k(t) = \frac{\sum_{i=1}^{m} TTI_i(t) * V_i(t)}{V_k(t)} \qquad \text{Equation 4.12}$$

where:

$TTI_k(t)$	=	TTI at time slice t for section k (no unit);
$TTI_i(t)$	=	TTI at time slice t for link i.
$V_i(t)$	=	VMT at time slice t for link i (vehicle-mile);
$\mathrm{V_k(t)}$	=	VMT at time slice t for section k (vehicle mile);
t	=	5-minute time slice, one of 288 in each day;
m	=	Total number of links in section k; and
k	=	Section k.

- *Adjustment for Missing Value*

  Factoring was performed to adjust missing data from links. VMT, VHT and delay were adjusted proportionally with the ratio of the missing link length to total section length. The requirement for factoring at this level was that at least half of the links in the section reporting data in the 5-minute interval. If no data is reported for the entire section at a 5-minute interval or less than half of the stations in the section reporting data, the entire section was set to missing/null values for the 5-minute interval. The reason for the "at least half" requirement is that the aggregated section level data should be able to reflect the travel in the entire section.

4.3.1.2 *Temporal aggregation for point sensors*

Several levels of temporal aggregation were performed to reduce data to the desired study periods. The designations of temporal periods are introduced below.

- **5-minute time slice**. There are 288 5-minute time slices in each day.
- **Peak periods**. Three hours (6:00 am to 9:00 am) of morning peak and three hours (4:00 pm to 7:00 pm) of evening peak are used. There are 72 5-minute time slices in the peak periods each day.
- **Work days**. Weekends and federally designated holidays were excluded from the analysis periods.

No commonly accepted definition of a peak period exists. Typical practice with archived traffic management center data is to divide the work days into five periods:

- Early morning
- Morning peak
- Midday
- Evening peak
- Late night

Both national congestion monitoring studies, Urban Mobility Report (UMR) and Mobility Monitoring Program (MMP), designate the morning peak from 6:00 am to 9:00

am and evening peak from 4:00 pm to 7:00 pm. Although the peak start and end time may vary for different freeway sections, the three hour morning or afternoon peak is believed to be long enough to capture the entire congested duration for most freeway sections. For the purpose of this study, capturing the exact morning or evening peak periods for each study section is not a concern. However, capturing the most congested duration for each study section so that little congestion was left uncounted is essential for the study.

Traffic patterns of holidays and weekends are very different from that of average work days. For the purpose of this study, holidays and weekends are excluded from the study.

The entire year of 2006 was used as the analysis period to avoid the seasonality effect which may exist in different urban areas. There were 251 work days in 2006. Therefore, for each study section, a matrix of 5-minute time slices with 288 × 251 cells exists. After the spatial aggregation, sectional level information of VMT, space mean speed, delay and TTI were available for each cell in the time matrix.

The following steps describe the procedures for temporal aggregation of the data.

1. Aggregating across work days

This step aggregates data from 251 work days into annual data for each section. The matrix of 288 × 251 5-minute time slices was collapsed into 288 time slices. Within the 288 5-minute time slices, the 72 slices in the peak periods were used in the next step of aggregation.

- *Sensor Data Aggregation*

  The 2006 total work day VMT and VHT at a 5-minute time slice were obtained by summing the section level VMT and VHT across all 251 work days (as shown in Equations 4.13 and 4.14). A 2006 work day space mean speed at a 5-minute time slice can be estimated by dividing the annual work day VMT with the annual work day VHT (as shown in Equations 4.15).

$$V_k^w(t) = \sum_{d=1}^{251} V_k^d(t) \qquad \text{Equation 4.13}$$

where:

$V_k^w(t)$ = 2006 total work day VMT at time slice t for section k (vehicle mile);

$V_k^d(t)$ = VMT at time slice t for section k in day d (vehicle mile);

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

d = Day d, one of 251 work days in 2006; and

k = Section k.

$$H_k^w(t) = \sum_{d=1}^{251} H_k^d(t) \qquad \text{Equation 4.14}$$

where:

$H_k^w(t)$ = 2006 total work day VHT at time slice t for section k (vehicle hour);

$H_k^d(t)$ = VHT at time slice t for section k in day d (vehicle hour);

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

d = Day d, one of 251 work days in 2006; and

k = Section k.

$$S_k^w(t) = \frac{V_k^w(t)}{H_k^w(t)} \qquad \text{Equation 4.15}$$

where:

$S_k^w(t)$ = 2006 work day space mean speed at time slice t for section k (mph);

$V_k^w(t)$ = 2006 total work day VMT at time slice t for section k (vehicle mile);

$H_k^w(t)$ = 2006 total work day VHT at time slice t for section k (vehicle hour);

w	=	Total work days in 2006;
t	=	5-minute time slice, one of 288 in each day;
d	=	Day d, one of 251 work days in 2006; and
k	=	Section k.

- *Performance Measure Aggregation*

  An annual work day total delay for 2006 at a 5-minute time slice was obtained by summing the section level delay across all 251 work days (as shown in Equation 4.16). An annual average work day TTI for 2006 at a 5-minute time slice was obtained by weighing the section level TTI of a work day with the section level VMT of the work day as the weighting factor (as shown in Equation 4.17). PTI was calculated at this step by obtaining the 95th percentile value of TTI out of the 251 TTI data points (as shown in Equation 4.18).

$$Delay_k^w(t) = \sum_{d=1}^{251} Delay_k^d(t) \qquad \text{Equation 4.16}$$

where:

$Delay_k^w(t)$	=	2006 total work day delay at time slice t for section k (vehicle hour);
$Delay_k^d(t)$	=	Delay at time slice t for section k in day d (vehicle hour);
w	=	Total work days in 2006;
t	=	5-minute time slice, one of 288 in each day;
d	=	Day d, one of 251 work days in 2006; and
k	=	Section k.

$$TTI_k^w(t) = \frac{\sum_{d=1}^{251} TTI_k^d(t) * V_k^d(t)}{V_k^w(t)} \qquad \text{Equation 4.17}$$

where:

$TTI_k^w(t)$	=	2006 work day TTI at time slice t for section k;

$TTI_k^d(t)$ = TTI at time slice t for section k in day d;

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

d = Day d, one of 251 work days in 2006; and

k = Section k.

$$PTI_k^w(t) = F^{95}\left[TTI_k^d(t)\right] \qquad \text{Equation 4.18}$$

where:

$PTI_k^w(t)$ = 2006 work day PTI at time slice t for section k;

$TTI_k^d(t)$ = TTI at time slice t for section k in day d;

$F^{95}\left[TTI_k^d(t)\right]$ = The 95th percentile TTI over the 251 work days in 2006;

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

d = Day d, one of 251 work days in 2006; and

k = Section k.

- *Adjustment for Missing Value*

  Factoring was performed to estimate sectional level missing/null values. These missing values are the results of detectors not reporting data for the entire section or less than half of detectors in the section reporting data for a 5-minute interval in a day. VMT and delay were adjusted up proportionally to the ratio of the number of missing days to total 251 days. The requirement for this factoring is that sectional data must be available for at least 200 work days out of 251 work days (80% of the 251 work days). If no data is reported for the entire section at a 5-minute interval for all 251 days or data is available for less than 80% of the 251 work days, the section is set to missing/null value for the 5-minute time slice in the annual work day value. The reason for the requirement is that the adjusted data should be able to reflect the travel for all work days in the year.

2. Aggregation across peak periods

This step aggregates data from the 72 5-minute annual data in the peak periods into one annual peak period data for each section.

- *Sensor Data Aggregation*

  Only VMT data was aggregated to this level. VMT was summed up for the 72 periods to obtain a 2006 annual work day peak period VMT. The process is illustrated in Equation 4.19.

$$V_k^w P = \sum_{t=1}^{72} V_k^w(t) \qquad \text{Equation 4.19}$$

where:

$V_k^w P$ = 2006 total work day VMT in the 6 hour peak periods for section k (vehicle mile);

$V_k^w(t)$ = 2006 total work day VMT at time slice t for section k (vehicle mile);

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

P = Total 6 hour peak periods; and

k = Section k.

- *Performance Measure Aggregation*

  A 2006 annual work day peak period performance measures (delay, TTI and PTI) were calculated. The 2006 annual work day peak period delay was calculated by summing the 72 5-minute periods to obtain the total peak period value (as shown in Equation 4.20). The 2006 annual work-day peak period TTI and PTI were obtained by weighing the TTI and PTI of a 5-minute time slice in the peak periods with the VMT of the 5-minute in the peak periods (as shown in Equation 4.21 and 4.22).

$$Delay_k^w P = \sum_{t=1}^{72} Delay_k^w(t) \qquad \text{Equation 4.20}$$

where:

$Delay_k^w P$ = 2006 total work day delay in the 6 hour peak periods for section k (vehicle hour);

$Delay_k^w(t)$ = 2006 total work day delay at time slice t for section k (vehicle hour);

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

P = Total 6 hour peak periods; and

k = Section k.

$$TTI_k^w P = \frac{\sum_{t=1}^{72} TTI_k^w(t) * V_k^w(t)}{V_k^w P} \qquad \text{Equation 4.21}$$

where:

$TTI_k^w P$ = 2006 work day TTI in the 6 hour peak periods for section k;

$TTI_k^w(t)$ = 2006 work day TTI at time slice t for section k;

$V_k^w(t)$ = 2006 total work day VMT at time slice t for section k (vehicle mile);

$V_k^w P$ = 2006 total work day VMT in the 6 hour peak periods for section k (vehicle mile);

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

P = Total 6 hour peak periods; and

k = Section k.

$$PTI_k^w P = \frac{\sum_{t=1}^{72} PTI_k^w(t) * V_k^w(t)}{V_k^w P} \qquad \text{Equation 4.22}$$

where:

$PTI_k^w P$ = 2006 work day PTI in the 6 hour peak periods for section k;

$PTI_k^w(t)$ = 2006 work day PTI at time slice t for section k;

$V_k^w(t)$ = 2006 total work day VMT at time slice t for section k (vehicle mile);

$V_k^w P$ = 2006 total work day VMT in the 6 hour peak periods for section k (vehicle mile);

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day;

P = Total 6 hour peak periods; and

k = Section k.

- *Adjustment for Missing Value*

  No adjustment for missing values is necessary at this step. Since one of the quality control rules (as described in the section 4.3.1.4) is that if any section has a missing/null value for the annual work day data at any 5-minute time slice in the peak periods, the section will be excluded from the study database.

4.3.1.3 *Spatial and temporal aggregation for toll tag data*

As introduced earlier, the toll tag system directly collects travel time, but does not have volume data available. The MMP estimated the volume number for all lanes in a direction and imputed into the 5-minute standardized dataset. AADT and a daily traffic distribution profile for each route section were used to estimate the volume in MMP.

1. Spatial aggregation

   The spatial aggregation process for toll tag data is similar to the process used for the point sensors. The only difference is that the toll tag data does not need the station level (Step 1) aggregation; the toll tag data is at the link level. The distance covered between adjoining toll tag reader sites in the toll tag data can be viewed as similar to the distance covered by a small link (as illustrated in Figure 4.10) with a point sensor. A single or multiple adjoining toll tag reader sites constitutes a study section.

2. Temporal aggregation

   Temporal aggregation process for toll tag data was identical to the process used for the point sensors.

4.3.1.4 *Data quality checking*

Extensive data quality checking was performed in the MMP during the data processing from the raw traffic operations center archives to the 5-minute lane-by-lane level (*5*). Some basic visual data quality checking was performed on aggregated section level 5-minute data in this research to ensure quality data. Travel rate (i.e., minutes per mile) distributions for the selected freeway sites were used for data quality checking and preliminary identification of travel time distribution patterns for these freeway segments. The travel rate data was obtained after the spatial and first step of temporal aggregation. Therefore, the travel rate is a section level 5-minute 2006 annual work day value. Equation 4.23 illustrates the travel rate calculation using speed calculated in Equation 4.15.

$$TR_k^w(t) = \frac{60}{S_k^w(t)} \qquad \text{Equation 4.23}$$

where:

$TR_k^w(t)$ = 2006 annual work day travel rate at time slice t for section k (minutes /mile);

$S_k^w(t)$ = 2006 work day space mean speed at time slice t for section k (mph);

w = Total work days in 2006;

t = 5-minute time slice, one of 288 in each day; and

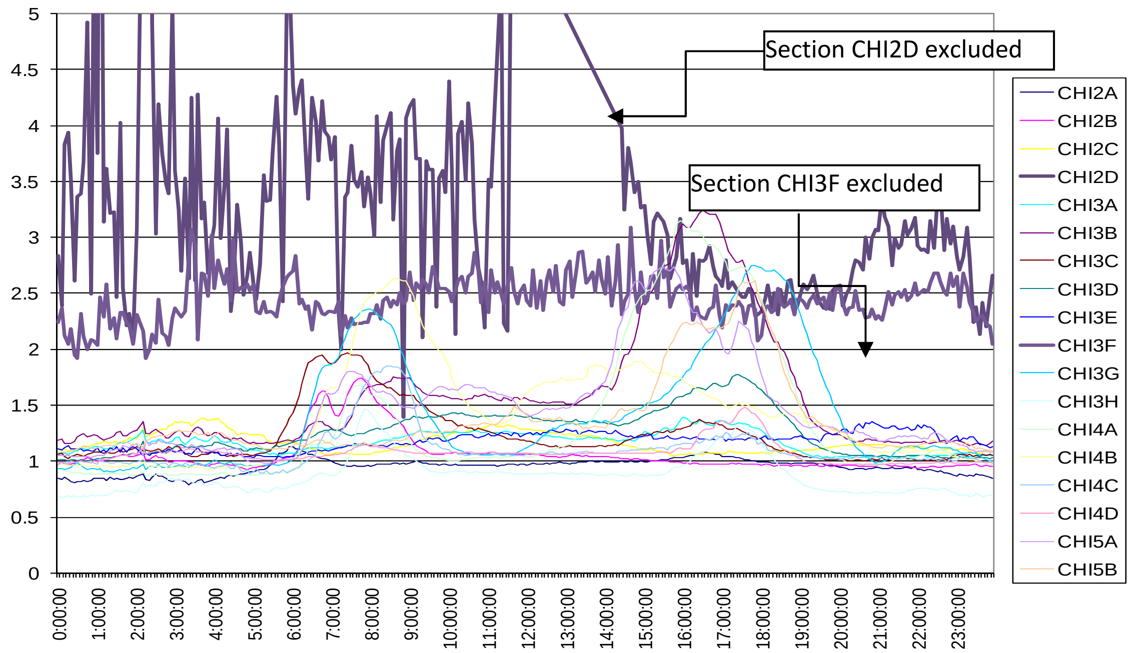
k = Section k.

Two general quality control rules were applied to the data quality checking on the sectional level 5-minute 2006 travel rate:

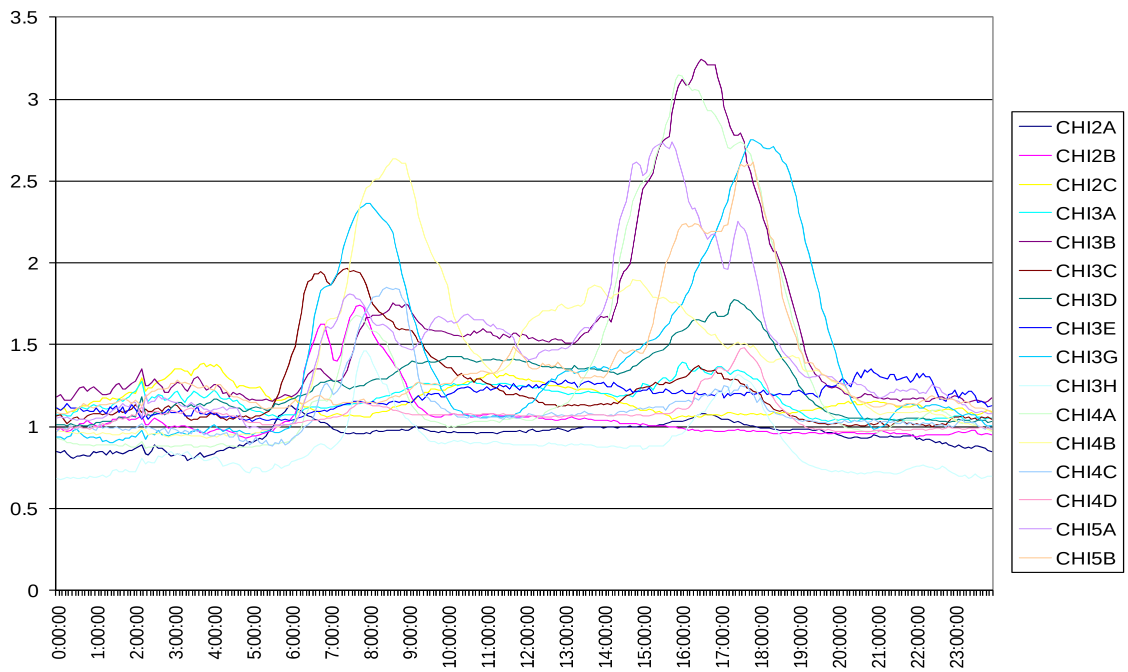
1. Exclude freeway sections that miss any sectional 5-minute aggregated travel rate data during the peak period or 1 hour of travel rate during off peak period for the entire section. This rule is to ensure that 1) no data is missing for the peak periods, and 2) although off-peak data was not used for final hypothesis testing, a significant amount of missing data for the entire year is a sign of detector failure.
2. Exclude freeway sections that have 2006 aggregated travel rate larger than 2 minutes/mile for the entire aggregated work day. This means the aggregated speed is less than 30 mph for all 288 5-minute time slices of the day. This rule is a reasonable check for U.S. freeway data.

Two sections (CHI2D and CHI3F) were excluded from the selected study sites after the quality checking. Section CHI2D had missing data from 11:40 am to 2:20 pm for all work days in 2006 and also had a travel rate larger than 2.0 for remaining 5-minute time slices. Section CHI3F also had a travel rate larger than 2.0 for the entire aggregated work day.

The travel rate distributions for the 149 study sections in seven urban areas using 2006 work day data are shown in Figures 4.11 to 4.17. These graphs were plotted to visually identify the section that failed the quality control rules. In the same time, the graphs also provide an exhibit of the regional pattern which may exist in the travel rate distribution. Of the original 149 study sites, 147 sites were used for hypothesis testing after the quality control.



(a) Before quality control



(b) After quality control by excluding CHI2D and CHI3F

FIGURE 4.11 Travel rate (minutes/mile) for Chicago area study sties.

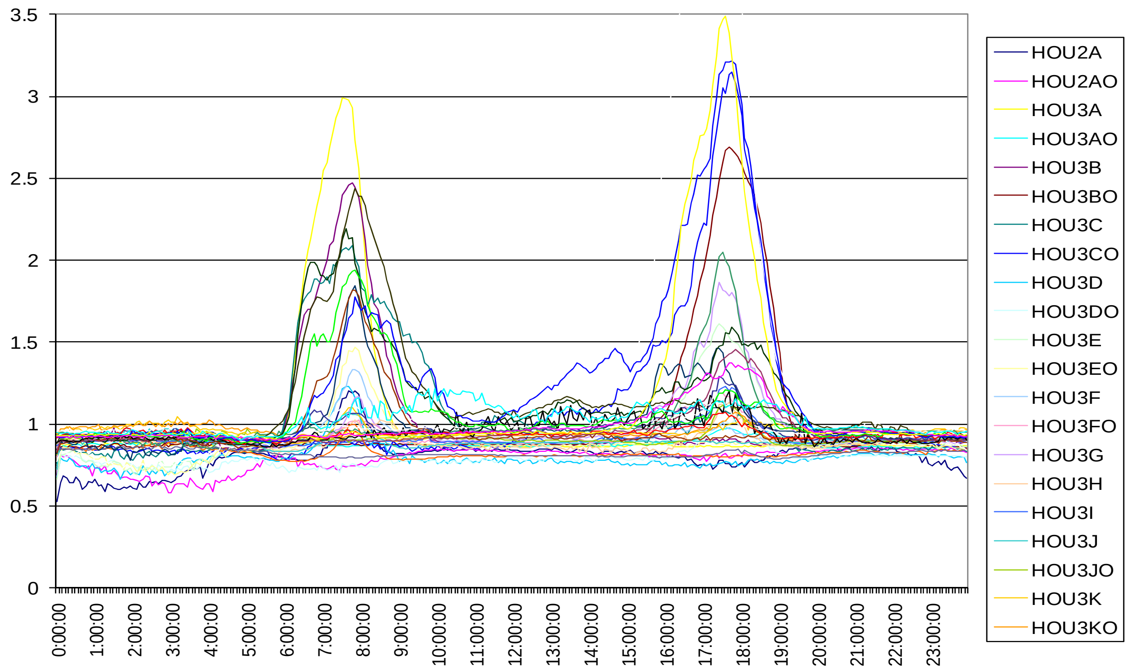


FIGURE 4.12 Travel rate (minutes/mile) for Houston area study sties.

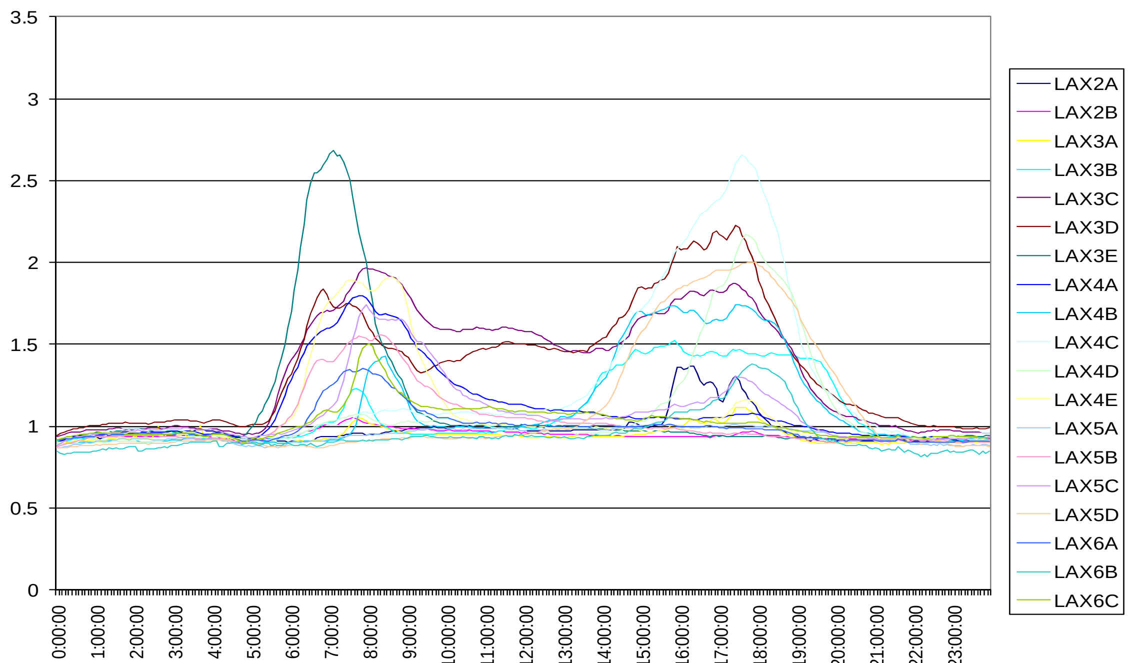


FIGURE 4.13 Travel rate (minutes/mile) for Los Angeles area study sties.

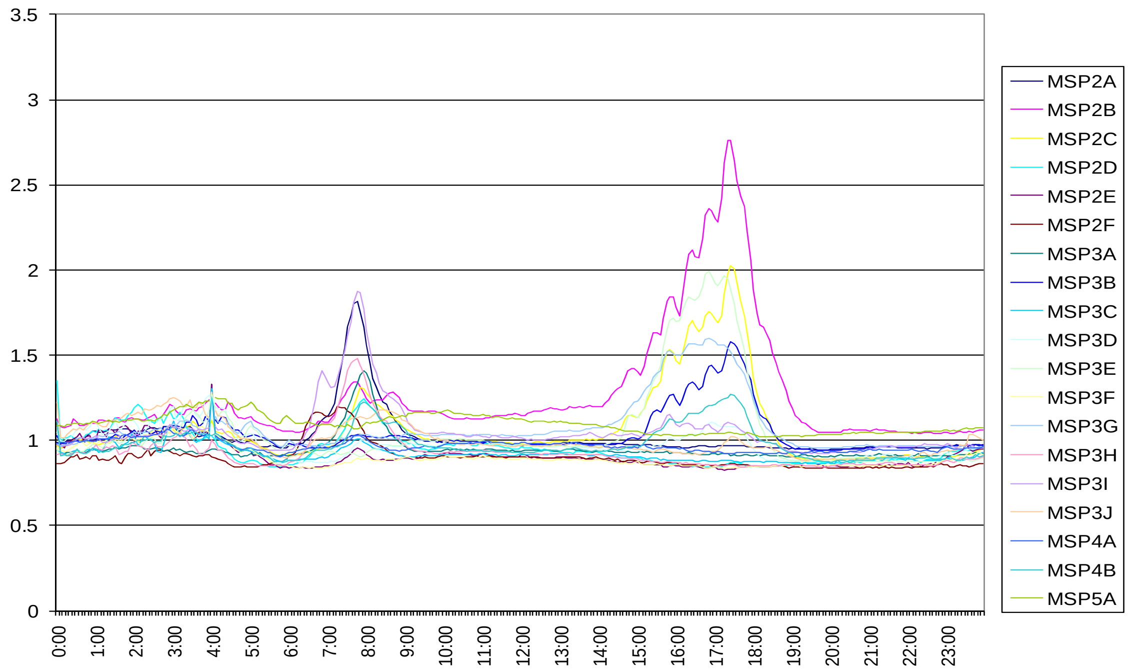


FIGURE 4.14 Travel rate (minutes/mile) for Minneapolis-St. Paul area study sties.

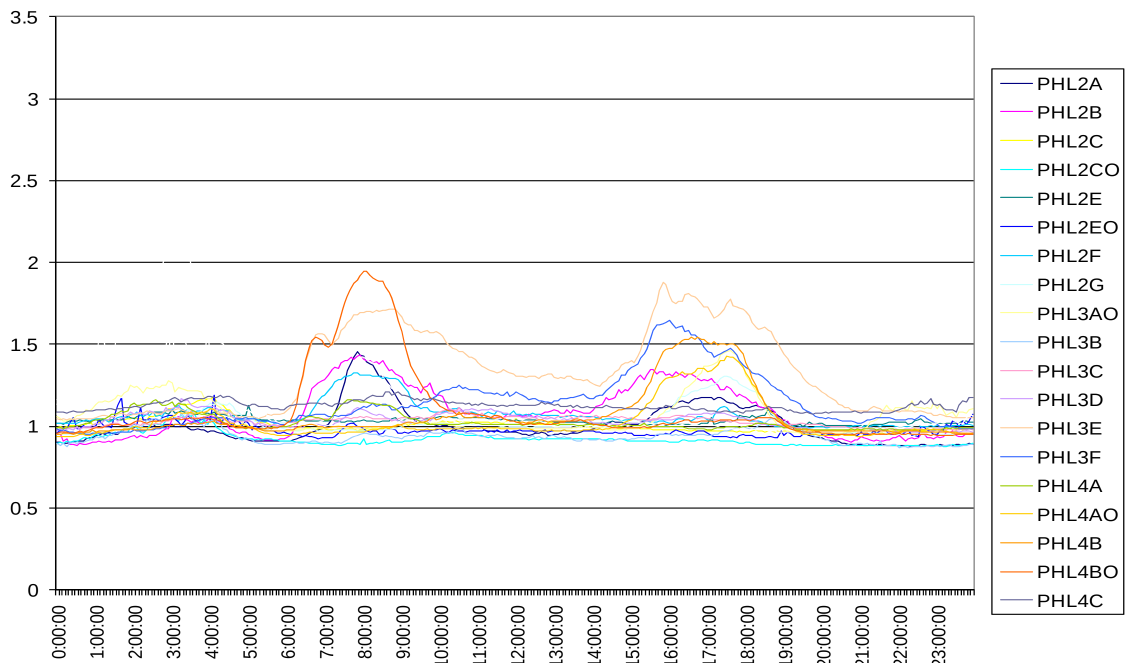


FIGURE 4.15 Travel rate (minutes/mile) for Philadelphia area study sties.

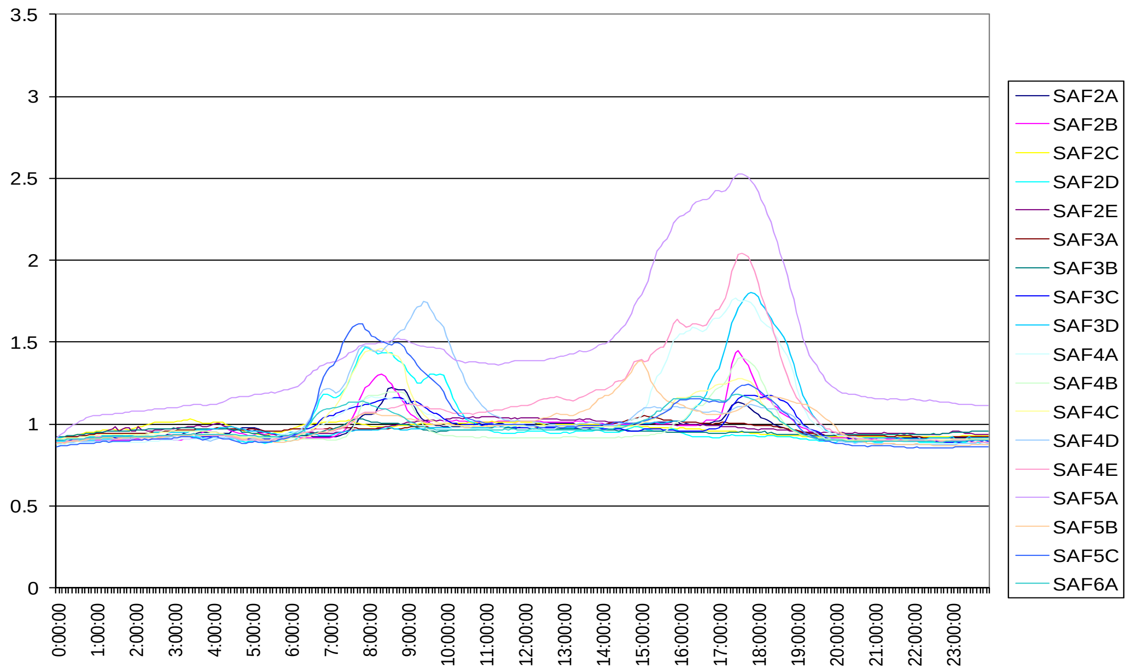


FIGURE 4.16 Travel rate (minutes/mile) for San Francisco area study sties.

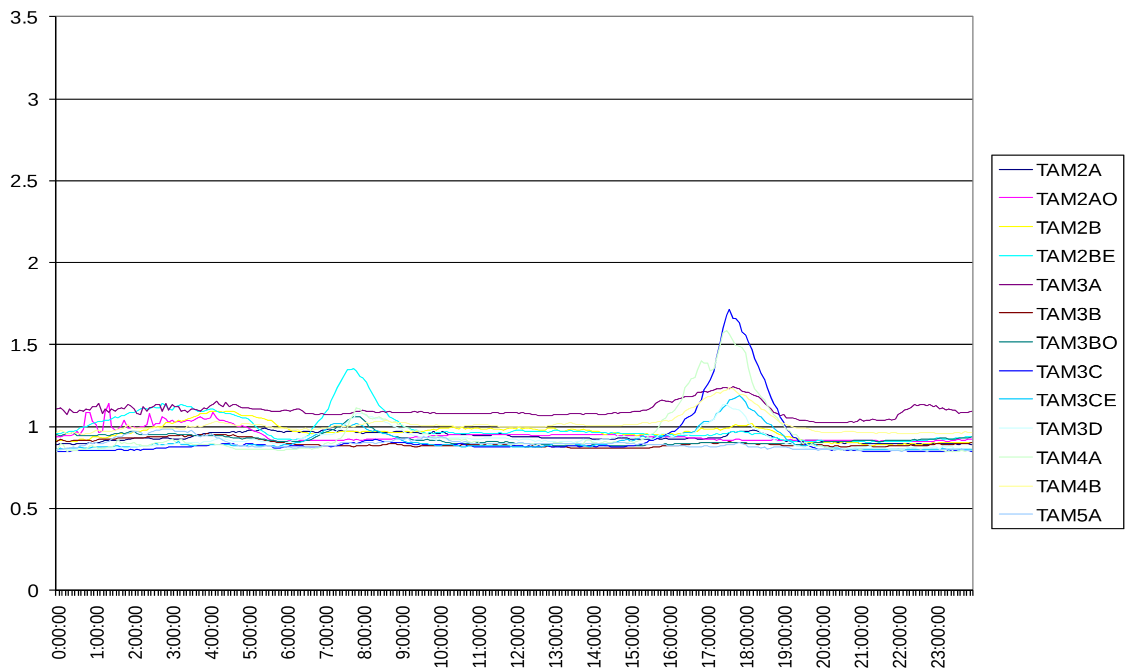


FIGURE 4.17 Travel rate (minutes/mile) for Tampa area study sties.

4.3.2 Data Aggregation for Hypothesis 2

Aggregation for hypothesis 2 can be viewed as a subset of the aggregation for hypothesis 1 because data from the same analysis year (2006) was used. Delay is the only performance measure that is relevant to hypothesis 2; the aggregated delay measure from hypothesis 1 can be used directly to test the hypothesis 2.

4.3.3 Data Aggregation for Hypothesis 3

All study sites for hypothesis 3 are located in the Houston metropolitan area. The toll tag data aggregation process (as introduced in section 4.3.1.3) was applied to the aggregate data for this hypothesis.

4.3.3.1 *Spatial and temporal aggregation*

The spatial aggregation process for this hypothesis was introduced in section 4.3.1.3. The temporal aggregation periods for this hypothesis constitute three analysis periods. Each analysis period constitutes three months,

- Analysis period 1: June, July and August of 2001
- Analysis period 2: June, July and August of 2002
- Analysis period 3: June, July and August of 2003

The temporal aggregation was performed to obtain a three-month average speed for each 5-minute daily time slice for the three analysis periods. The 5-minute time slices were further separated into three time periods. The designations of the three time periods are,

- Off peak period: Six hours of early morning (12:00 am to 6:00 am) and five hours of late night (7:00 pm to 12:00 am)
- Peak period: Three hours (6:00 am to 9:00 am) of morning peak and three hours (4:00 pm to 7:00 pm) of evening peak

- Peak hour: One hour (7:00 am to 8:00 am) of morning peak hours and one hour (5:00 pm to 6:00 pm) of evening peak hours

4.3.3.2 *Data quality control*

Visual data quality checking was performed on aggregated section level 5-minute speed data in this research to ensure quality data. Section 8 (the section of northbound Sam Houston Tollway from Memorial Dr. to US 290) was excluded from the study sites. This section missed more than half of the data for analysis period 1 and analysis period 2. Therefore, this site is not useful to perform a before and after quasi-experiment study which requires examining the trend for the three analysis periods.

4.4 Final Datasets

The final datasets for testing the three hypotheses are introduced below.

4.4.1 Final Datasets for Testing Hypothesis 1

Hypothesis 1 is to test whether the rankings of congestion measures hold steady across different congestion thresholds.

Delay, TTI and PTI for the 2006 annual work day peak periods were calculated for all 147 study sites. The delay value was divided by section length to obtain a normalized delay value (delay per mile) so that the value can be compared among sections. These three measures (delay/mile, TTI, and PTI) for the 147 study sites were ranked by the severity of congestion with the rank 1 being the most congested section.

The final datasets for hypothesis 1 are the rank values for the three performance measures under the eight congestion threshold scenarios (as described in section 3.3.1.3). A total of 24 (3 times 8) datasets constitute the final datasets for hypothesis 1 testing.

4.4.2 Final Datasets for Testing Hypothesis 2

Hypothesis 2 is to test whether the relationship of delay under different congestion thresholds is non-linear and can be expressed in a quadratic form.

Calculated as a subset of hypothesis 1, the 2006 delay per mile for the annual work day peak period was calculated for the seven uniformed congestion threshold scenarios (as introduced in section 3.3.2.3) for the 147 sites.

The final datasets for hypothesis 2 are the delay per mile value in thousand vehicle hours per mile for 147 study sites. A total of 7 datasets constitute the final datasets for hypothesis 2 testing.

4.4.3 Final Datasets for Testing Hypothesis 3

Hypothesis 3 is to test whether speed limit affects travel time distribution for both peak and off-peak period.

The average speed for each 5-minute time slice of the day for the three analysis periods (before, during and after periods) and nine study sites was calculated for hypothesis 3 testing. These dataset were separated by the time periods for testing the effect of peak period, off-peak period, and peak hour.

A total of 27 (3 times 9) datasets for each of the three time periods constitute the final datasets for hypothesis 3 testing.

CHAPTER V
RESULTS AND FINDINGS

This chapter documents the results and findings of the three hypothesis tests. The results and findings are interpreted to answer the research questions listed in Chapter III. The sections below present the detailed results by each hypothesis.

5.1 Hypothesis 1

A linear regression analysis was performed to test the hypothesis 1 on whether the rankings of congestion measures for freeway sections hold steady across different congestion thresholds. In the regression analysis, the relationships tested is whether freeway congestion ranking values obtained from an alternative threshold speed scenario form a linear relationship with those from the 60 mph baseline scenario. The regressed slope was compared to 1 using the 95% confidence interval.

5.1.1 Results for Delay per Mile

The rankings of the delay per mile value for the 147 study sections under eight congestion threshold scenarios were used for the regression analysis. To test the null hypothesis, a test statistic of the *t* distribution (Equation 5.1) with n-2 degrees of freedom was calculated (*41*). The estimate of the slope $\hat{\beta}$ and the standard error of the slope $se(\hat{\beta})$ were needed for the test statistic. A α value of 0.05 was used for this hypothesis testing.

$$T_0 = \frac{\hat{\beta}-1}{se(\hat{\beta})} \qquad \text{Equation 5.1}$$

where:

T_0	=	t-statistic value for the null hypothesis;
$\hat{\beta}$	=	the estimate of the slope; and
$se(\hat{\beta})$	=	the standard error of the slope.

One would reject $H_{01:}\ \beta = 1$ if $|T_0| > t_{\frac{\alpha}{2},n-2}$, which means the test statistic is outside of the confidence interval of $(\hat{\beta} - 1)$. For this study, the t distribution $T_{\frac{\alpha}{2},n-2}$ was $T_{0.025,145}$ (which is approximately 1.96).

Table 5.1 presents the regression scenarios, the estimate and the standard error of the regression slope, t statistic calculated from Equation 5.1, and *p*-value.

TABLE 5.1 Hypothesis 1 Testing Results Using Delay per Mile Performance Measure

Regression Scenarios	$\hat{\beta}$	$se(\hat{\beta})$	T_0	*p*-value
55 mph vs. 60 mph	0.99869	0.00423	-0.30969	0.7572
50 mph vs. 60 mph	0.99675	0.00667	-0.48726	0.6268
45 mph vs. 60 mph	0.99554	0.00781	-0.57106	0.5688
40 mph vs. 60 mph	0.99348	0.00943	-0.69141	0.4904
35 mph vs. 60 mph	0.98998	0.01168	-0.85788	0.3924
30 mph vs. 60 mph	0.98454	0.01450	-1.06621	0.2881
Non-uniform vs. 60 mph	0.99319	0.00964	-0.70643	0.4811

P-values for all regression scenarios listed in Table 5.1 are greater than the α value 0.05. Therefore, the hypothesis of $\beta = 1$ or $R_i = R_{60}$ cannot be rejected for all congestion threshold scenarios. This result indicates that congestion rankings using delay per mile with the alternative threshold speeds are equal to the rankings with the 60 mph baseline threshold speed with a 95% confidence level.

Figure 5.1 shows the scatter plots of rankings by baseline and alternative thresholds. All plots are fitted with the regression line and the 95% prediction limits. Note that "Rank_D60" for the X-axis represents the rankings of 147 freeway sections using delay per mile under the 60 mph baseline threshold. Y-axis is for the rankings by alternative thresholds. The last two digits of the variable stand for the threshold speed used.

The following findings are interpreted from Figure 5.1 and Table 5.1.

1. When the alternative congestion threshold speed is close to the 60 mph baseline threshold, there is less fluctuation of the data around the regression line. This can be proven by the regression results in Table 5.1. The closer the congestion threshold speed is to the 60 mph, the closer $\hat{\beta}$ is to 1 and the smaller value of $se(\hat{\beta})$ is. Even for the "least close" scenario (30 mph vs. 60 mph), the rankings are equal within the 95% confidence interval.
2. There is less variability in the rankings for freeway sections that are either ranked very high or very low under all congestion threshold speeds (Figure 5.1). In other words, the sections that are ranked high (the most congested) and low (the least congested) under the 60 mph baseline case remain similar ranking positions under other congestion threshold scenarios. Using the travel time distribution graph (as shown in Figure 5.2) to illustrate this finding, the most congested sections have not only longer congested periods (duration) but also higher travel time values (magnitude). Less congested sections have shorter congested periods and lower travel time values.

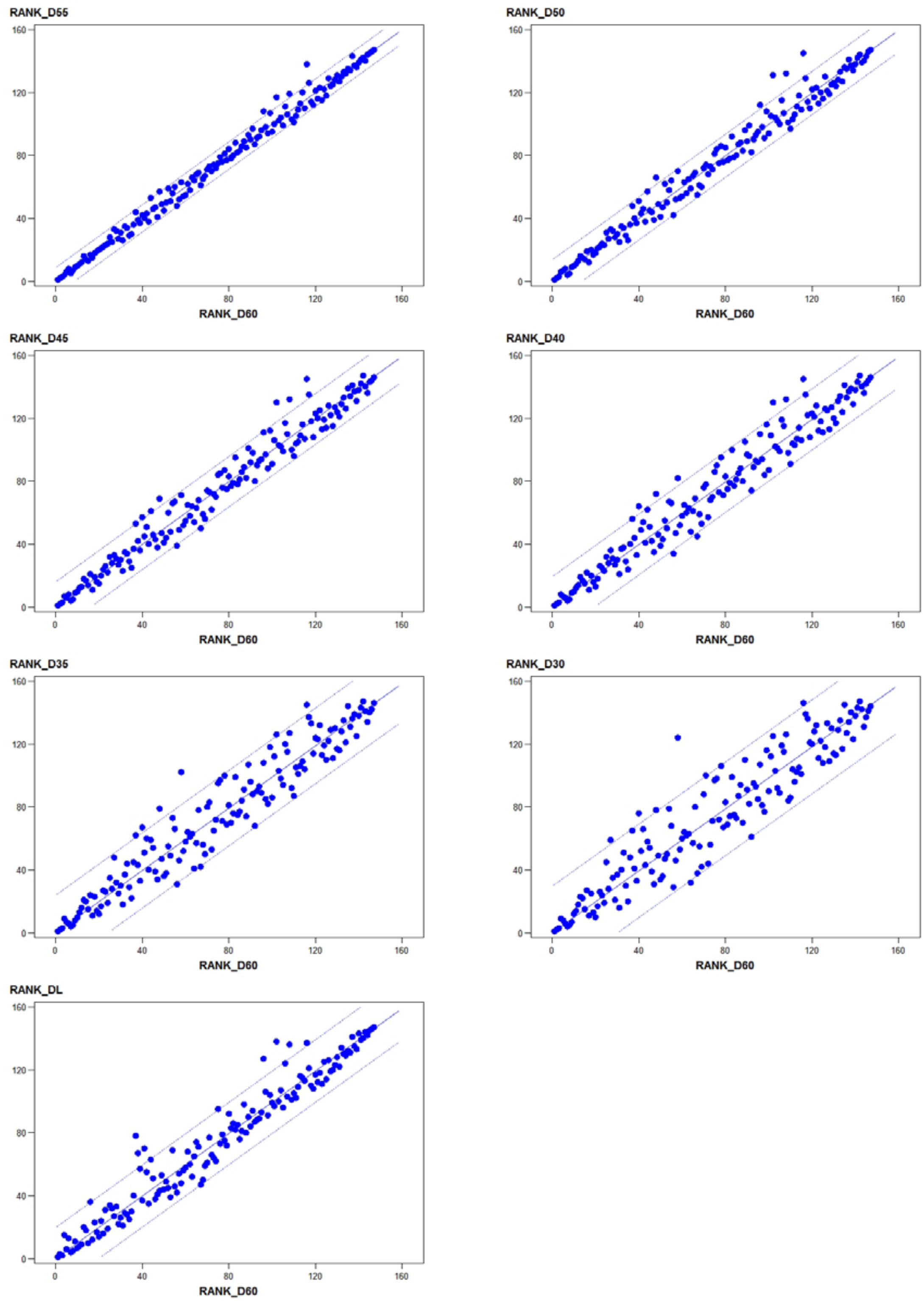


FIGURE 5.1 Comparison of rankings of baseline vs. alternative scenarios on delay per mile.

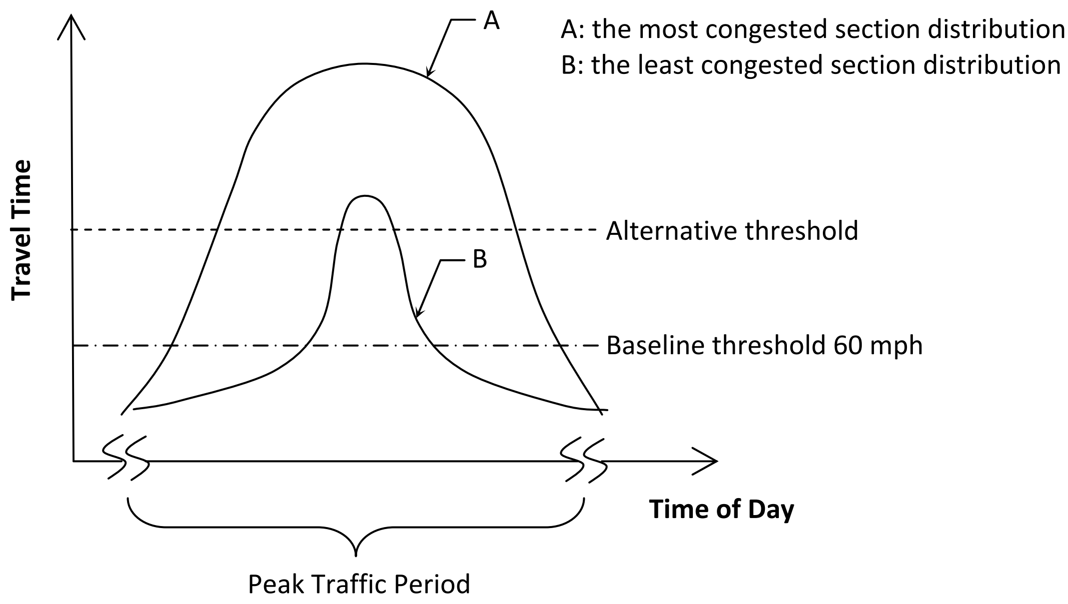


FIGURE 5.2 Travel time distribution examples for the most and least congested sections.

3. The regression of the non-uniform congestion threshold (variable name "Rank_DL") with the 60 mph baseline scenario is a mix of 55 mph with 60 mph, 45 mph with 60 mph, and 35 mph with 60 mph. The scatter plot shows a relatively close fit to the regression line with some data points above the upper prediction limit. This observation can be explained by the area type labeled scatter plot (Figure 5.3). Note that area types 1, 2 and 3 are CBD, urban and suburban types, respectively. It was found that 78 out of the 147 sections were in the suburban area type (area type 3) that used 55 mph as the congestion threshold speed. Therefore, these 78 sections had a relatively close fit with the baseline scenario because of the closeness between 55 mph to 60 mph (as explained in the finding 1). For the 56 sections in the urban area type (area type 2) that used 45 mph as the congestion threshold speed, these data points departed further away from the regression line. Because these sections were evaluated under a lower congestion threshold speed, the rankings for these sections became lower, i.e.,

less congested. This is reflected in Figure 5.3 with these data points moving upwards from the regression line and close to the upper prediction limit. The same findings can be observed on the 13 CBD sections (area type 1 in Figure 5.3). These CBD data points moved even further upwards from the regression line due to the further lower congestion threshold speed of 35 mph. The differences in the rankings for some of these CBD sections were so large that they fell outside of the upper prediction limit, an area where cannot be explained by the regression model.

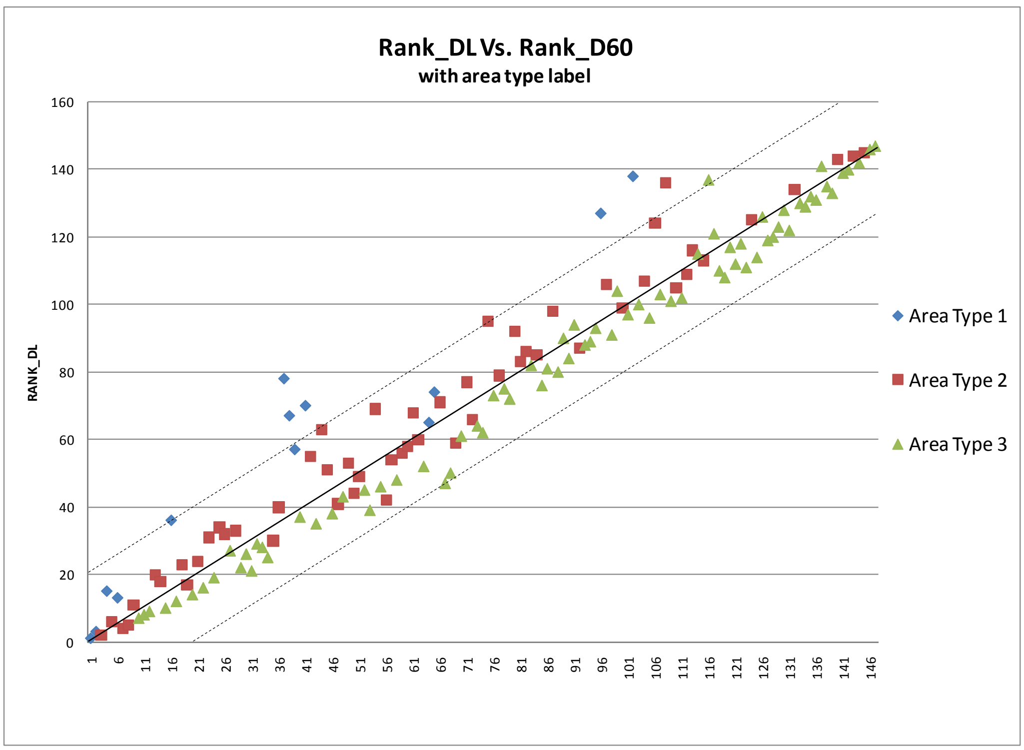


FIGURE 5.3 Scatter plot of non-uniform thresholds vs. the 60 mph threshold with area type label for delay per mile ranking.

4. For the six uniform threshold regression scenarios shown in Figure 5.1, there are more data points that are above the upper prediction limit than there are data

points below the lower prediction limit. Figure 5.4 illustrates the areas in related to the regression line.

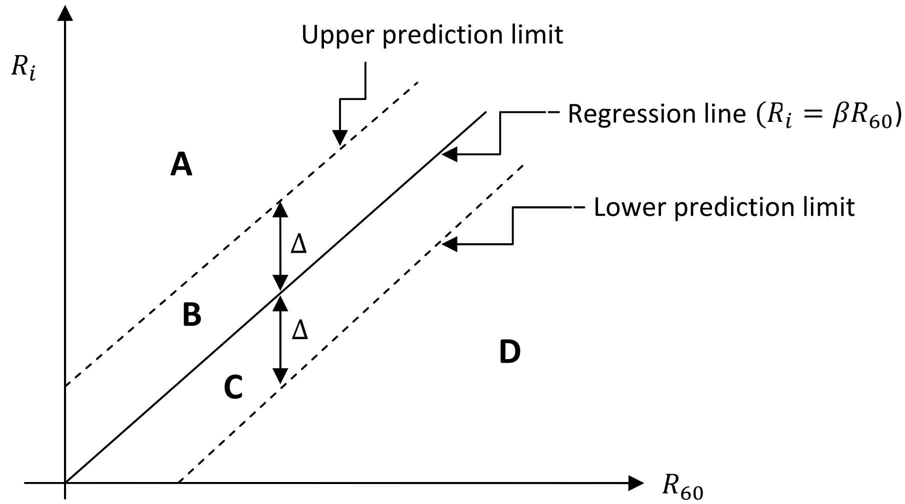


FIGURE 5.4 Illustration of the area outside of the prediction limits.

The first quadrant in Figure 5.4 can be divided into four areas (A, B, C and D) by the regression line and two prediction limit lines. The two prediction limit lines can be expressed as $R_i = \beta R_{60} \pm \Delta$. Δ is the prediction interval and a function of R_{60}, model variance, sample size and the significance level. The four areas (A, B, C and D) can be defined as follows.

- Area A is the area above the upper prediction limit and can be expressed mathematically as $R_i > \beta R_{60} + \Delta$. With $\beta \approx 1$, area A becomes $R_i > R_{60} + \Delta$. Area A indicates that the ranking values from an alternative congestion threshold are one Δ greater than those from the 60 mph baseline threshold.
- Area D is the area below the lower prediction limit and can be expressed mathematically as $R_i < \beta R_{60} - \Delta$. With $\beta \approx 1$, the area D becomes $R_i < R_{60} - \Delta$. Area D indicates that the ranking values from an alternative

congestion threshold are one Δ less than those of from the 60 mph baseline threshold.

- Areas B and C are the area within the prediction limits. With $\beta \approx 1$, this area can be expressed as $R_{60} - \Delta \leq R_i \leq R_{60} + \Delta$, which means the ranking values from an alternative congestion threshold are within one Δ both directions of the regression line.

The regression results show that there are more data points in area A than those in area D. This means that there were more freeway sections with ranking values at least one Δ greater (less congested) than those one Δ less (more congested) when using alternative threshold speeds.

The finding can also be illustrated in the travel time distribution graph in Figure 5.5. Travel time distribution type C illustrates those freeway sections with ranking values at least one Δ greater (less congested) using alternative threshold speeds. Conversely, travel time distribution type A illustrates those sections with ranking values at least one Δ less (more congested) using alternative threshold speeds. The regression findings show that there were more type C distributions than the type A distributions.

What are the common characteristics of these sections? What made these sections fall outside the prediction limits? And is the reason that more data points were above the upper prediction limit than the data points below the lower prediction limit simply the randomness of the selection set or do the findings apply to other sections as well? These questions regarding the sections that fell outside of the prediction limits warrant future research.

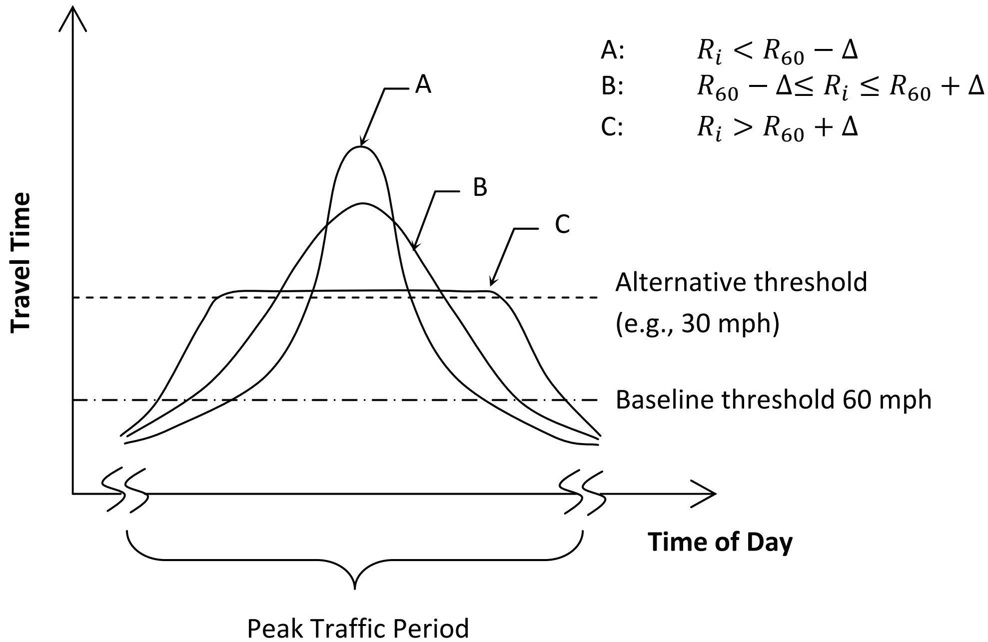


FIGURE 5.5 Travel time distribution examples for explaining congestion ranking differences.

5.1.2 Results for Travel Time Index (TTI)

The rankings of the TTI value for the 147 study sections under eight congestion threshold scenarios were used for regression analysis. To test the null hypothesis, test statistics of the *t* distribution (as shown in Equation 5.1) with n-2 degrees of freedom were estimated. A α value of 0.05 was chosen for this hypothesis testing.

Table 5.2 lists the regression scenarios, the estimate and the standard error of the regression slope, t statistic calculated from Equation 5.1, and *p*-value. The result shows that the hypothesis testing of $\beta = 1$ or $R_i = R_{60}$ cannot be rejected for all congestion threshold scenarios using TTI as the performance measure. Or one could say that the result shows congestion rankings from alternative threshold speeds are equal to the rankings under the 60 mph baseline threshold with a 95% confidence level.

TABLE 5.2 Hypothesis 1 Testing Results Using Travel Time Index Performance Measure

Regression Scenarios	$\hat{\beta}$	$se(\hat{\beta})$	T_0	P-value
55 mph vs. 60 mph	0.99815	0.00503	-0.36779	0.7136
50 mph vs. 60 mph	0.99421	0.00890	-0.65056	0.5164
45 mph vs. 60 mph	0.98866	0.01243	-0.91231	0.3631
40 mph vs. 60 mph	0.98224	0.01553	-1.14359	0.2547
35 mph vs. 60 mph	0.97244	0.01929	-1.42872	0.1552
30 mph vs. 60 mph	0.95993	0.02319	-1.7279	0.0861
Non-uniform vs. 60 mph	0.97679	0.01773	-1.30908	0.1926

Figure 5.6 shows the scatter plots of rankings by baseline and alternative thresholds. All plots are fitted with the regression line and the 95% prediction limits. Note that “Rank_T60” for the X-axis represents the rankings of 147 freeway sections using TTI under the 60 mph baseline threshold. Y-axis is for the rankings by alternative thresholds. The last two digits of the variable name indicates the threshold speed used.

The following findings can be seen from Figure 5.6 and Table 5.2.

1. When the alternative congestion threshold speed is close to the 60 mph baseline threshold, there is less fluctuation of the data around the regression line. This finding is similar to finding 1 of section 5.1.1 except that the prediction limits are wider compared to the same regression scenario using delay per mile as the performance measure. This may be because delay per mile includes both average speed and volume in the variables (as illustrated in equation 3.6) while TTI has only average speed as the variable (as illustrated in equation 3.8). The volume variable in the delay function would give another measure to quantify the congestion intensity and thus better explain the data. Therefore, the prediction limits of the regression line using delay per mile as the performance measure might be expected to be narrower than those of the TTI plots.
2. There is less variability in the rankings for the freeway sections that either ranked very high or very low under all congestion threshold speeds (Figure 5.6). This

finding is also similar to finding 2 in section 5.1.1. This finding again shows that the most congested sections have longer congested periods (duration) and higher travel time values (magnitude). Less congested sections have shorter congested periods and lower travel time values.

3. Regarding the non-uniform regression scenario (variable name “Rank_TL”), similar finding as in the section 5.1.1 can be observed. Figure 5.7 shows the scatter plot with data points for the three area types. The data points for CBD (area type 1) are generally on top; urban area (area type 2) is in the middle; and suburban area (area type 3) is at the bottom. This is reflected in Figure 5.7 where data points (from area type 3) fit closely right below the regression line while the data points (from area 1 and 2) above the regression line are further away from the regression line and close to the upper prediction limit. Some data points are even outside of the limit. As explained in section 5.1.1, this is because different threshold speeds were used for each section according to their area type.
4. There are more data points that are above the upper prediction limit than there are data points below the lower prediction limit for the six uniform threshold regression scenarios (Figure 5.6), similar to the delay per mile finding in section 5.1.1.

These findings again warrant more future research. The question raised in section 5.1.1 also applies to the finding using TTI as the performance measure.

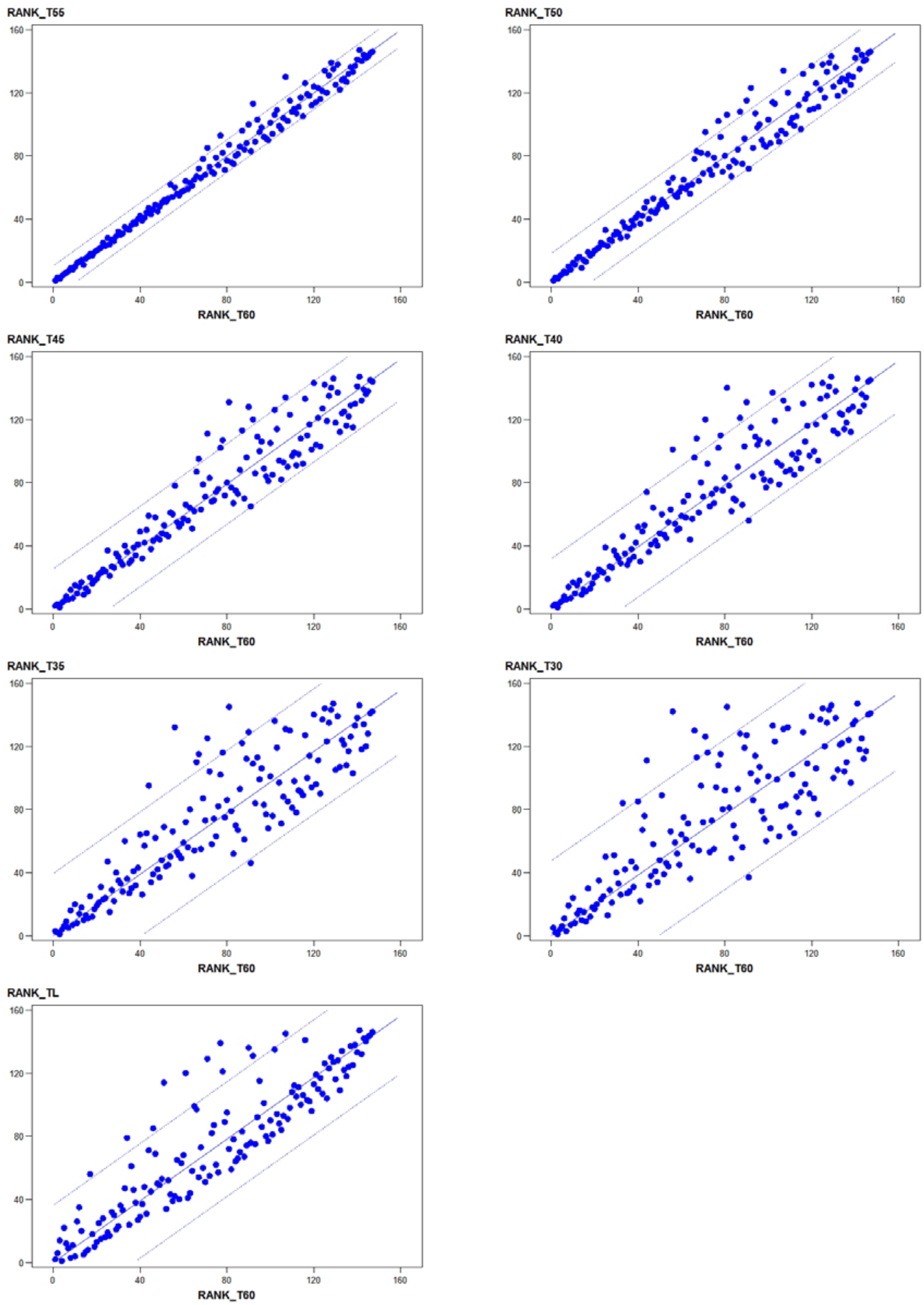


FIGURE 5.6 Comparison of rankings of baseline vs. alternative scenarios on Travel Time Index.

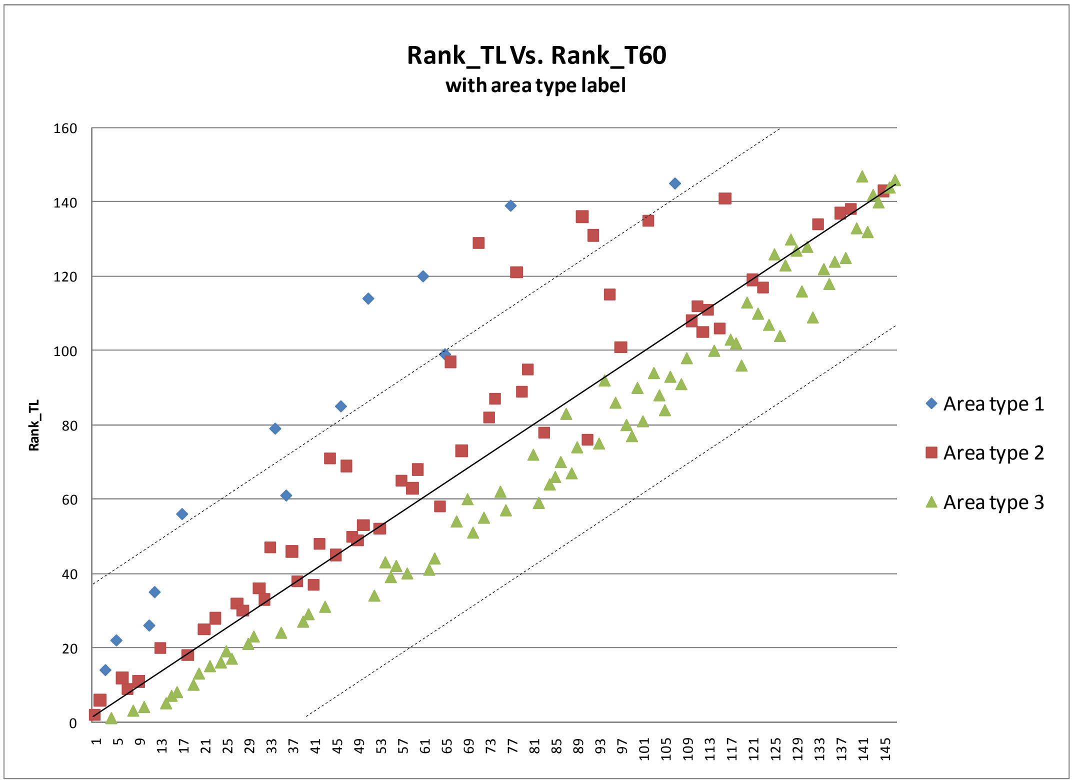


FIGURE 5.7 Scatter plots of non-uniform thresholds vs. the 60 mph threshold with area type label for Travel Time Index ranking.

5.1.3 Results for Planning Time Index (PTI)

Similar to delay per mile and TTI, the rankings of the PTI value for the 147 study sections under eight congestion threshold scenarios were used for regression analysis. To test the null hypothesis, test statistic of the *t* distribution (as shown in Equation 5.1) with n-2 degrees of freedom was estimated. A α value of 0.05 was chosen for this hypothesis testing.

Table 5.3 lists the regression scenarios, the estimate and standard error of the regression slope, t statistic calculated from Equation 5.1, and *p*-value. The result shows that the hypothesis of $\beta = 1$ or $R_i = R_{60}$ cannot be rejected for all congestion threshold cases using PTI as the performance measure. Or one could say that the result shows congestion rankings from alternative congestion thresholds are equal to the rankings from the 60 mph baseline threshold at the 5% significance level.

TABLE 5.3 Hypothesis 1 Testing Results Using Planning Time Index Performance Measure

Regression Scenarios	$\hat{\beta}$	$se(\hat{\beta})$	T_0	P-value
55 mph vs. 60 mph	0.99888	0.00392	-0.28571	0.7755
50 mph vs. 60 mph	0.99591	0.00748	-0.54679	0.5854
45 mph vs. 60 mph	0.99100	0.01108	-0.81227	0.4180
40 mph vs. 60 mph	0.98560	0.01399	-1.02931	0.3050
35 mph vs. 60 mph	0.97644	0.01786	-1.31915	0.1892
30 mph vs. 60 mph	0.96313	0.02226	-1.65633	0.0998
Non-uniform vs. 60 mph	0.97830	0.01715	-1.26531	0.2078

Figure 5.8 shows the scatter plots of rankings by baseline and alternative thresholds. All plots are fitted with the regression line and the 95% prediction limits. Note that "Rank_P60" for the X-axis represents the rankings of 147 freeway sections using PTI under the 60 mph baseline threshold. Y-axis is for the rankings by alternative thresholds. The last two digits of the variable name indicates the threshold speed used.

The following findings can be seen from Figure 5.8 and Table 5.3:

1. When the alternative congestion threshold speed is close to the 60 mph baseline threshold, there is less fluctuation of the data around the regression line. This finding is similar to both delay per mile in section 5.1.1 and TTI in section 5.1.2. The prediction limit ranges for PTI are similar to that of TTI.

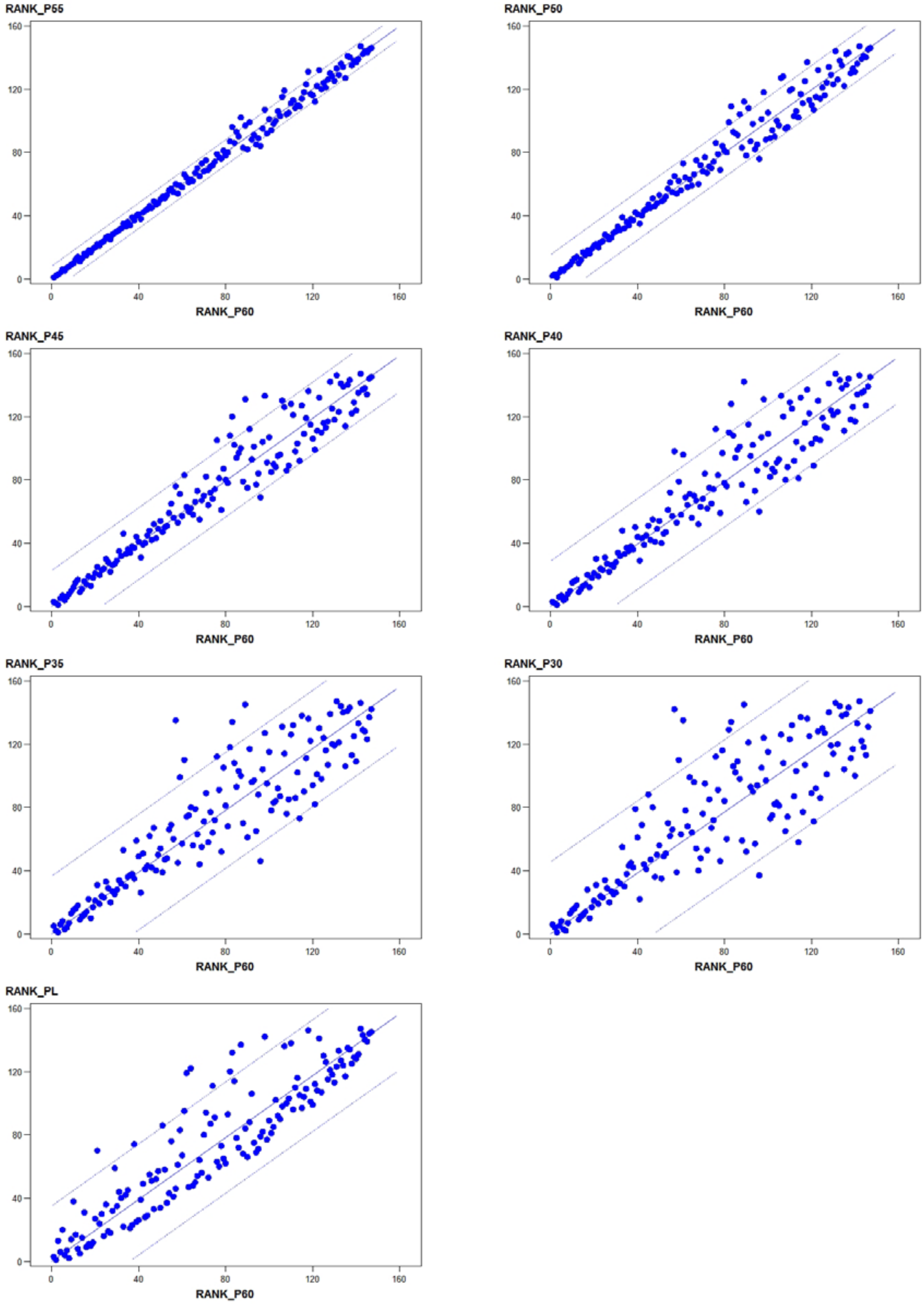


FIGURE 5.8 Comparison of rankings of baseline vs. alternative scenarios on Planning Time Index.

2. It can also be observed that there is less variability in the rankings for the freeway sections that are either ranked very high or very low under all congestion threshold speeds (Figure 5.8). This finding is also similar to the finding 2 in section 5.1.1 and section 5.1.2, again indicating that the most congested sections have not only longer congested periods (duration) but also higher travel time values (magnitude). The least congested sections are exactly the opposite. Not only such sections have shorter congested periods but also lower travel time values.
3. Regarding the non-uniform regression scenario (variable name "Rank_PL"), the similar finding as in the section 5.1.1 and 5.1.2 can be observed. Figure 5.9 shows the area type labeled scatter plot. The data points for the three area types separated into three layers. The data points for CBD (area type 1) are generally on top; urban area (area type 2) is in the middle; and suburban area (area type 3) is at the bottom. This is reflected in Figure 5.9 where data points (from area type 3) fit closely right below the regression line while the data points (from area types 1 and 2) above the regression line are further away from the regression line and close to the upper prediction limit. Some data points are outside of the limit. As explained in section 5.1.1, this is because different threshold speeds were used for each section according to their area type.
4. There are more data points that are above the upper prediction limit than there are data points below the lower prediction limit for the six uniform threshold regression scenarios (Figure 5.8), similar to the delay per mile and TTI findings.

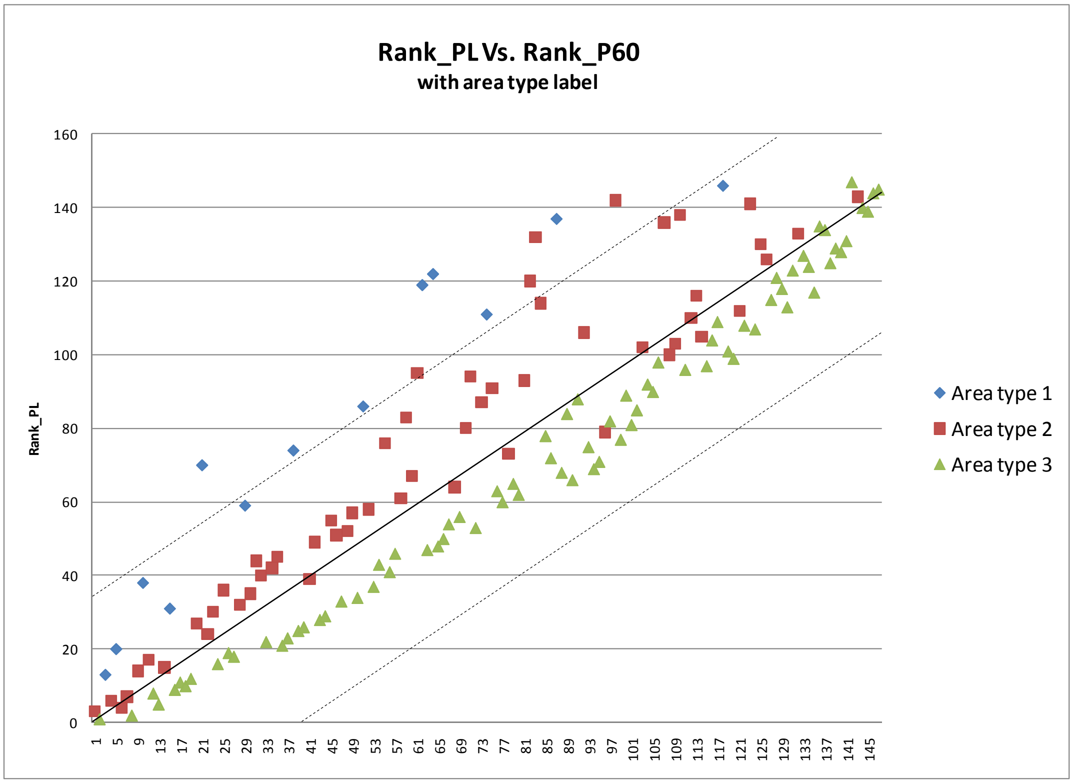


FIGURE 5.9 Scatter plots of non-uniform thresholds vs. the 60 mph threshold with area type label for Planning Time Index ranking.

As in sections 5.1.1 and 5.1.2, this finding again warrants more future research. The question raised in section 5.1.1 also applies to the finding using PTI as the performance measure.

5.2 Hypothesis 2

As introduced in section 3.3.2.4, a quadratic regression was performed to test the hypothesis 2 on whether the relationship of delay under different congestion thresholds is non-linear and can be expressed in a quadratic form. In the regression analysis, two relationships tested are 1) whether the regression parameter (γ) for the quadratic term is 0, which means the relationship between the two delay values obtained with different congestion thresholds is linear, and 2) how well the quadratic line fits the data if a non-linear relationship exists between the two values of delay. The hypothesis is expressed in Equation 3.10.

The delay per mile values for the 147 study sections and eight congestion threshold scenarios were used for regression analysis. The 60 mph congestion threshold speed was used as the baseline scenario. P-value for the null hypothesis $\gamma = 0$ was used to test the first relationship of whether the regression parameter for the quadratic term is 0. The coefficient of determination R^2 was used to judge the adequacy of the regression model or how well the quadratic line fits the data. Table 5.4 lists the estimated values for the regression parameters α, β, and γ, p-value for testing $\gamma = 0$ and R^2 for each regression scenario.

TABLE 5.4 Hypothesis 2 Testing Results

Regression Scenarios	α	β	γ	p-value	R^2
55 mph vs. 60 mph	-0.52069	0.84892	0.00069	<.0001	0.9977
50 mph vs. 60 mph	-0.53523	0.70043	0.00132	<.0001	0.9921
45 mph vs. 60 mph	-0.35439	0.55347	0.00190	<.0001	0.9839
40 mph vs. 60 mph	-0.06603	0.40439	0.00243	<.0001	0.9721
35 mph vs. 60 mph	0.30536	0.25506	0.00287	<.0001	0.9558
30 mph vs. 60 mph	0.71439	0.11396	0.00313	<.0001	0.9354

As presented in Table 5.4, for all regression scenarios, the p-values for the null hypothesis $\gamma = 0$ are less than 0.0001, which leads to reject the null hypothesis with a 95% confidence level. The relationship between the values of delay per mile from different thresholds is non-linear. The R^2 values for all regression scenarios show that the model accounts for above 93% of the variability in the data, which means the quadratic regression line fits the data well.

Figures 5.10 through 5.15 show the scatter plot and fitted regression line for each regression scenario. Note that “DLY60_PM” for the X-axis represents the delay per mile from the 60 mph baseline threshold in 1,000 vehicle hour per mile. The number in the variable name indicates the congestion threshold speed used.

The following findings are interpreted from Figures 5.10 through 5.15 and Table 5.4.

1. The closer the alternative congestion threshold speed is to the baseline speed of 60 mph, the less fluctuation of the data is to the regression line. This relationship is supported by the R^2 values listed in Table 5.4. The R^2 values become smaller when the alternative congestion threshold speed is further away from the baseline scenario. This means the model explains the data better when the alternative threshold speed is closer to the baseline speed.
2. The further away the alternative threshold speed is from the 60 mph baseline threshold, the more quadratic the regression line becomes. This observation is shown in the γ values listed in Table 5.4. The γ values become larger when the alternative congestion threshold speed is further away from the 60 mph baseline scenario. For the regression scenario of 55 mph vs. 60 mph, the regression line is almost linear. However, for all regression scenarios, the null hypothesis ($\gamma = 0$) is rejected at a significant level of 0.05, which means the quadratic term cannot be ignored.
3. The 147 data points in Figures 5.10 through 5.15 seem to cluster into three groups: 1) the delay per mile value less than 40,000 vehicle hours, 2) the delay per mile value between 40,000 and 100,000 vehicle hours, and 3) the delay per mile value larger than 100,000 vehicle hours. Separate analyses of each group may provide more insight into the common characteristics of each group. Since the delay value is the annual work day total, the observation could provide some basis for the dividing values when grouping freeway sections for severity of congestion using annual work day delay.

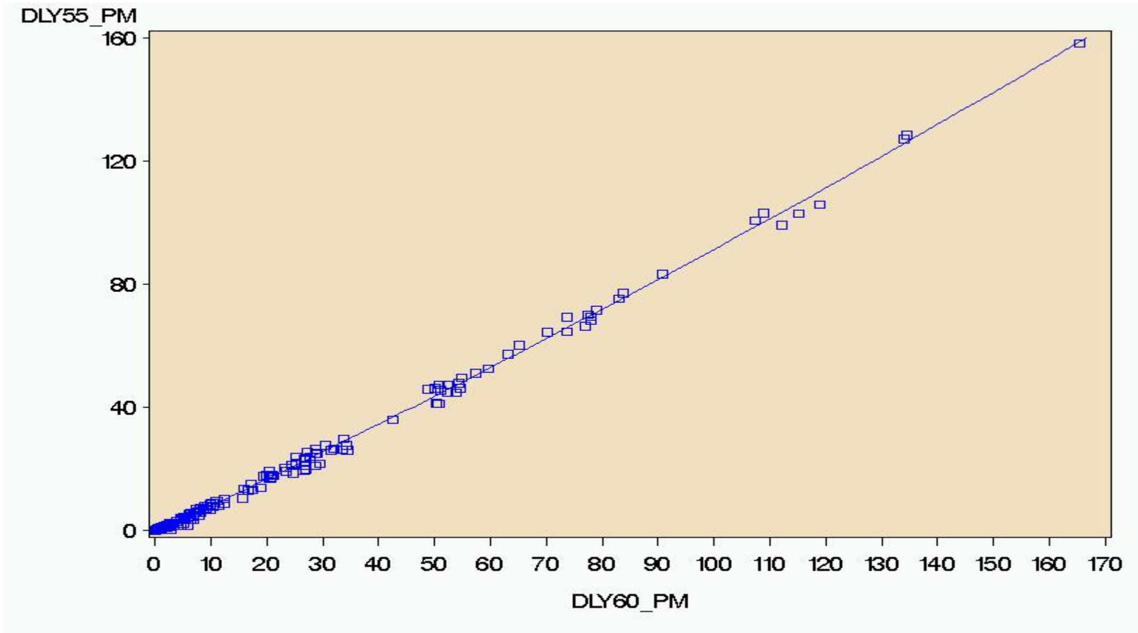


FIGURE 5.10 Regression line of delay per mile using 55 mph vs. 60 mph.

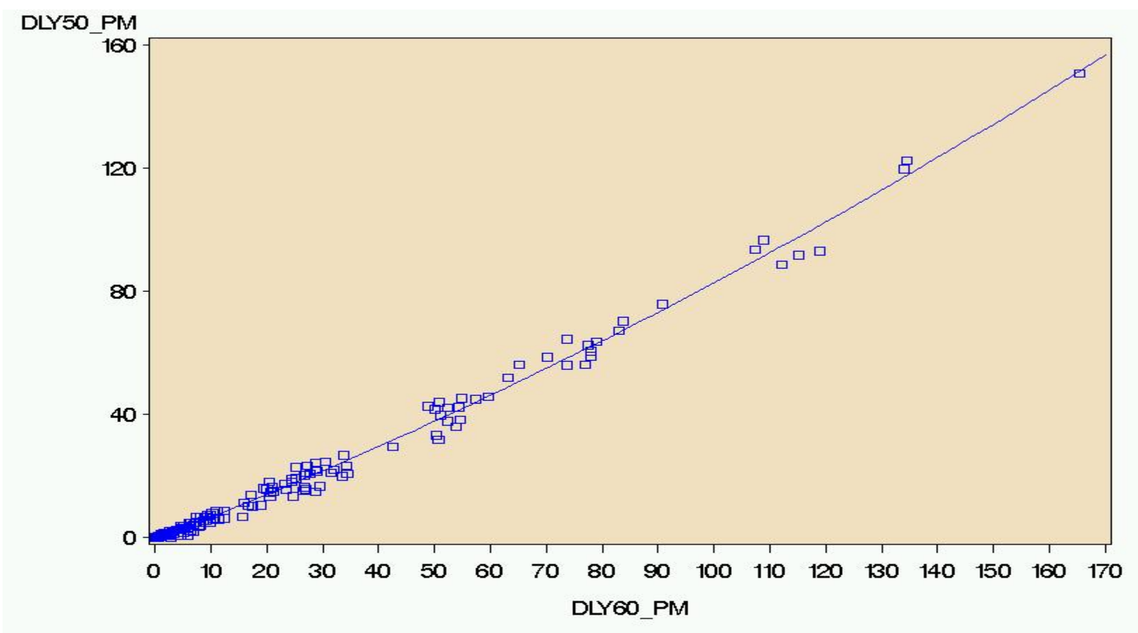


FIGURE 5.11 Regression line of delay per mile using 50 mph vs. 60 mph.

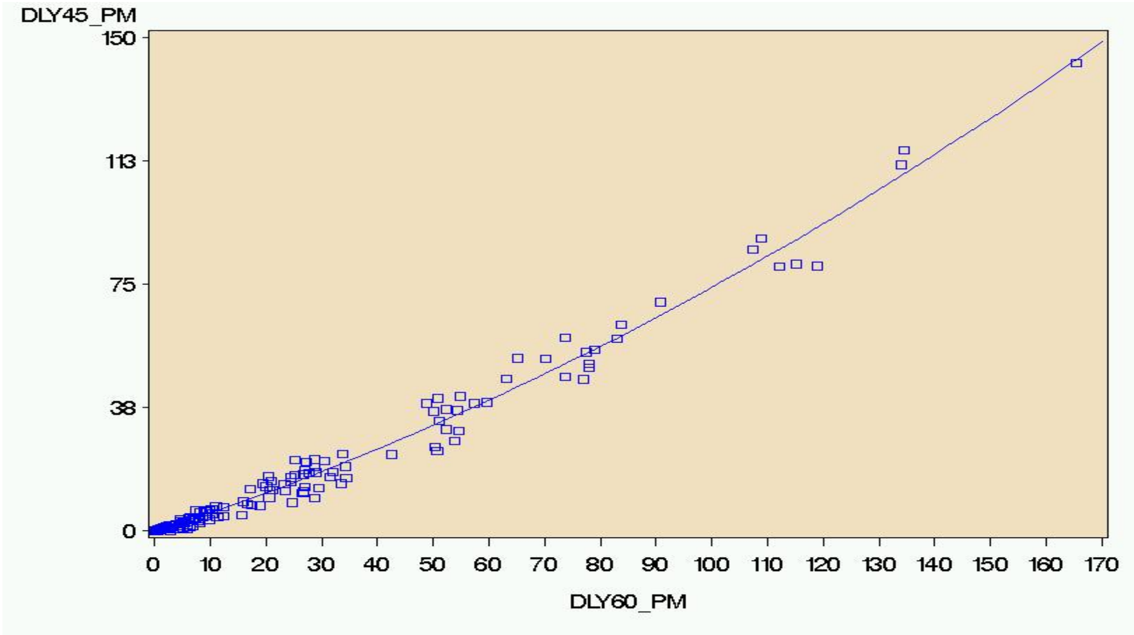


FIGURE 5.12 Regression line of delay per mile using 45 mph vs. 60 mph.

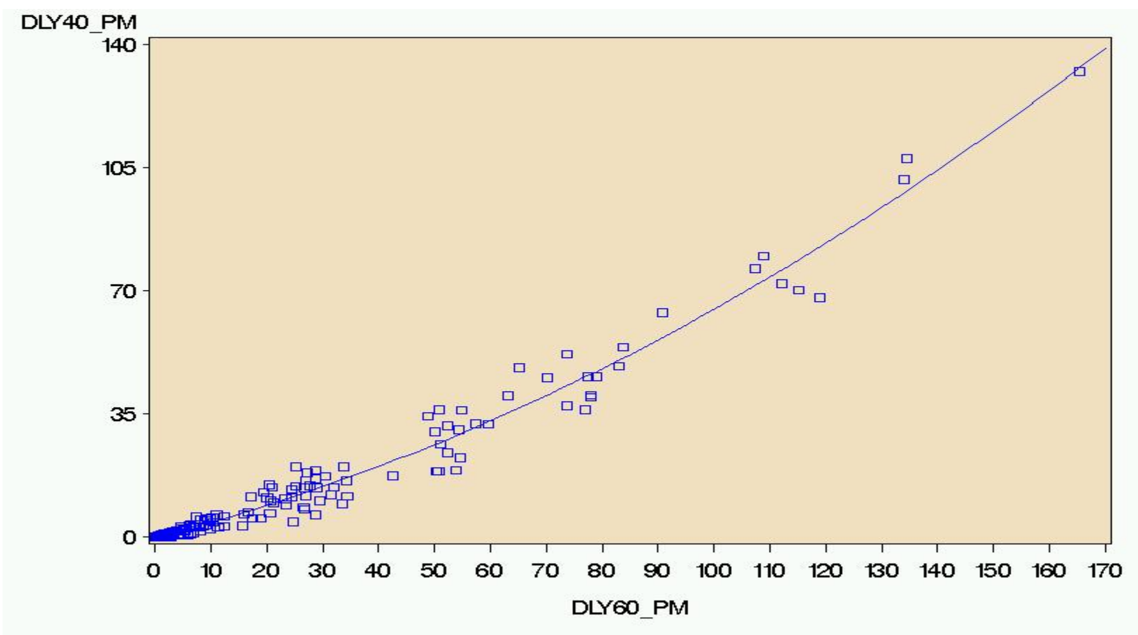


FIGURE 5.13 Regression line of delay per mile using 40 mph vs. 60 mph.

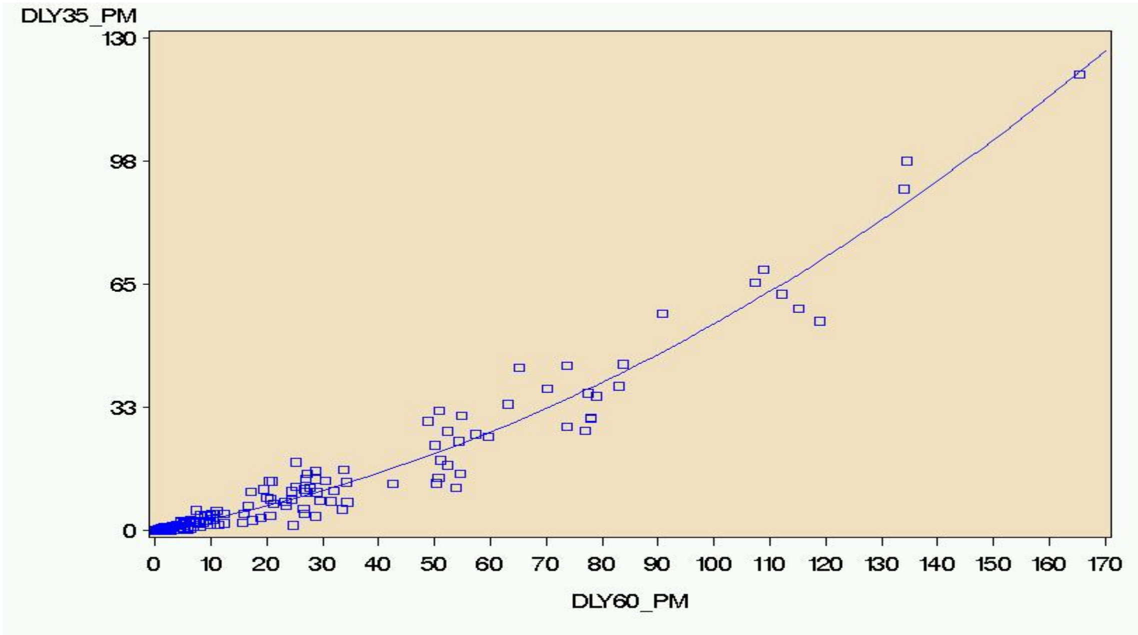


FIGURE 5.14 Regression line of delay per mile using 35 mph vs. 60 mph.

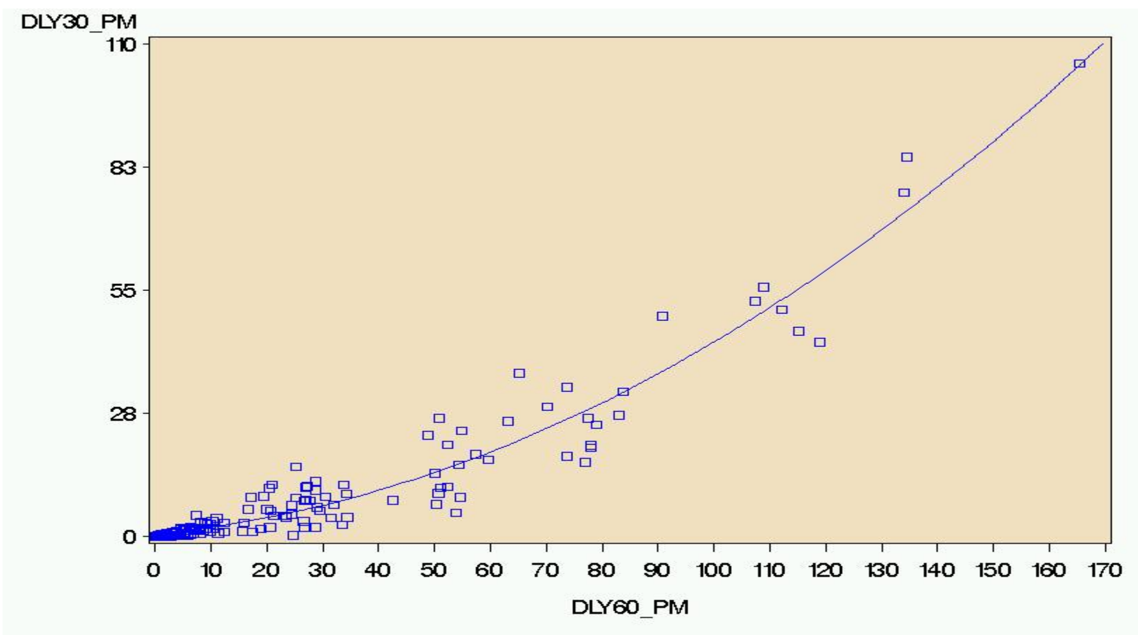


FIGURE 5.15 Regression line of delay per mile using 30 mph vs. 60 mph.

Using the regressed models and plotting all six regression lines together in Figure 5.16, the relationship of delay per mile from different congestion thresholds can be easily observed. However, to understand the reduction rate of delay as the congestion threshold reduces, knowing the amount of the delay is not enough. Figure 5.17 further shows the percentage of the delay per mile value from an alternative threshold compared to that of the 60 mph threshold. This figure reveals that the reduction rate of delay per mile for the more congested sections (right end of Figure 5.17) is much slower than the less congested sections (left end).

As shown in Figure 5.17, the percentage of delay per mile from all alternative congestion thresholds increases with the congestion level. In the case of alternative threshold of 35 mph, the delay per mile ranges from about 33% to 78% of the 60 mph threshold value. For a lightly congestion section (left end of Figure 5.17), only 33% of the delay from the 60 mph threshold remains when using 35 mph as the threshold. For a heavily congested section (right end of Figure 5.17), about 78% of the delay from the 60 mph threshold still remains when using 35 mph as the threshold.

Furthermore, it can be concluded that 1) the more congested a section is, the less influential the threshold becomes, and 2) for very congested sections, most of the delay is associated with speeds below 30 mph.

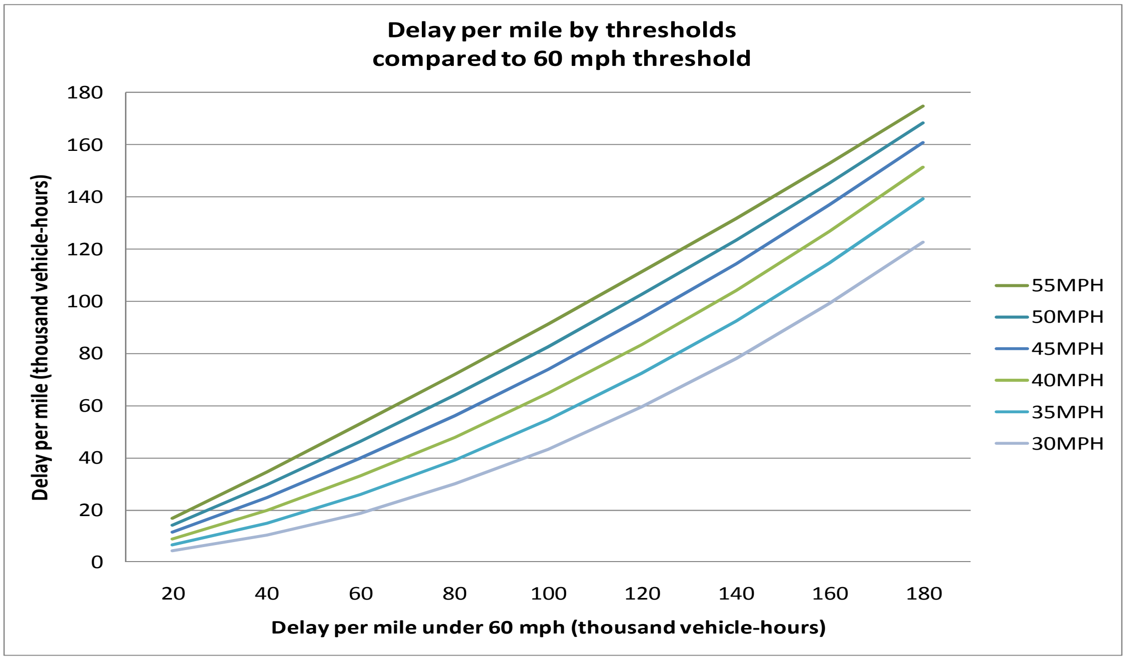


FIGURE 5.16 Delay per mile under an alternative threshold compared to the 60 mph.

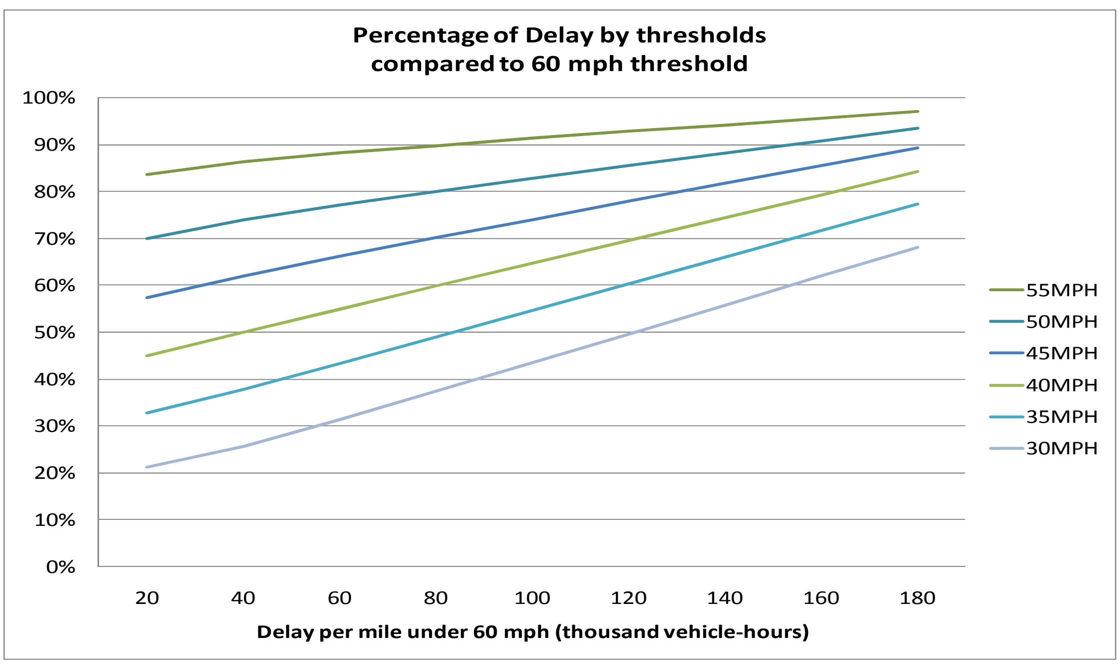


FIGURE 5.17 Percentage of delay per mile under an alternative threshold compared to the 60 mph.

5.3 Hypothesis 3

Hypothesis 3 is to test whether the speed limit affects travel time distribution for both peak and off-peak periods. A historic event of area wide speed limit change in Houston Metropolitan area provides a before-and-after case for testing the hypothesis 3. As introduced in section 3.3.3, four analysis steps were performed: 1) exploring the trend of speed distribution and travel growth for the study sections in the "before," "during" and "after" periods, 2) comparing the differences between the trends of speed distribution and travel growth at the time of speed limit change or the "during" period, 3) identifying rival events or ruling out the confounding factors, and 4) drawing conclusions on whether the speed limit change resulted in a change in the speed distribution.

5.3.1 Speed Distribution for the Three Analysis Periods

The average speeds for the three analysis periods were plotted together to visually assess any trend that may exist. The three month aggregated speeds for each 5-minute time slice in a day were plotted (Figures 5.18 through 5.26) for the nine study sections and the three analysis periods: 1) the before period (June through August of 2001), 2) the "during" period (June through August of 2002), and 3) the after period (June through August of 2003).

As shown in Figures 5.18 through 5.26, the average speeds of the early morning and late night of the "before," "during" and "after" periods were clearly different in all study sections. The "before" period showed the highest average speed, the "during" period showed the lowest speed, and the average speed for the "after" period was between the "before" and "during" periods. This trend of average speeds for the off-peak period was the same as that of the posted speed limits during the three analysis periods. However, the speed differences between the analysis periods were smaller than the posted speed limit changes for the three analysis periods. For example, the posted speed limit difference between the "before" and "after" periods was 5 mph, however, the average speed difference between the "before" and "after" periods was much smaller than 5 mph for all study sections during the two off-peak periods. The trend of the average speeds for the midday period is not as clear as the other two off-peak periods. The trend seems varied by study section and hour during the midday period. Judged from the average speed, some sections seem fairly congested during the midday period.

The trend of average speed for the morning and afternoon peak periods seems varied by section. Seven sections had their lowest speed in 2002 during the peak periods; sections 2 and 5 had the lowest speed in 2003.

It should also be noted that the average speeds for the early morning and late night periods were much higher than 55 mph for all study sections during the 55 mph speed limit effective period. Although speed enforcement and how closely people obey the speed limit is beyond the scope of this study, the observation that the free flow speed is higher than the speed limit provides evidence-based information about whether it is appropriate to use speed limit as congestion threshold.

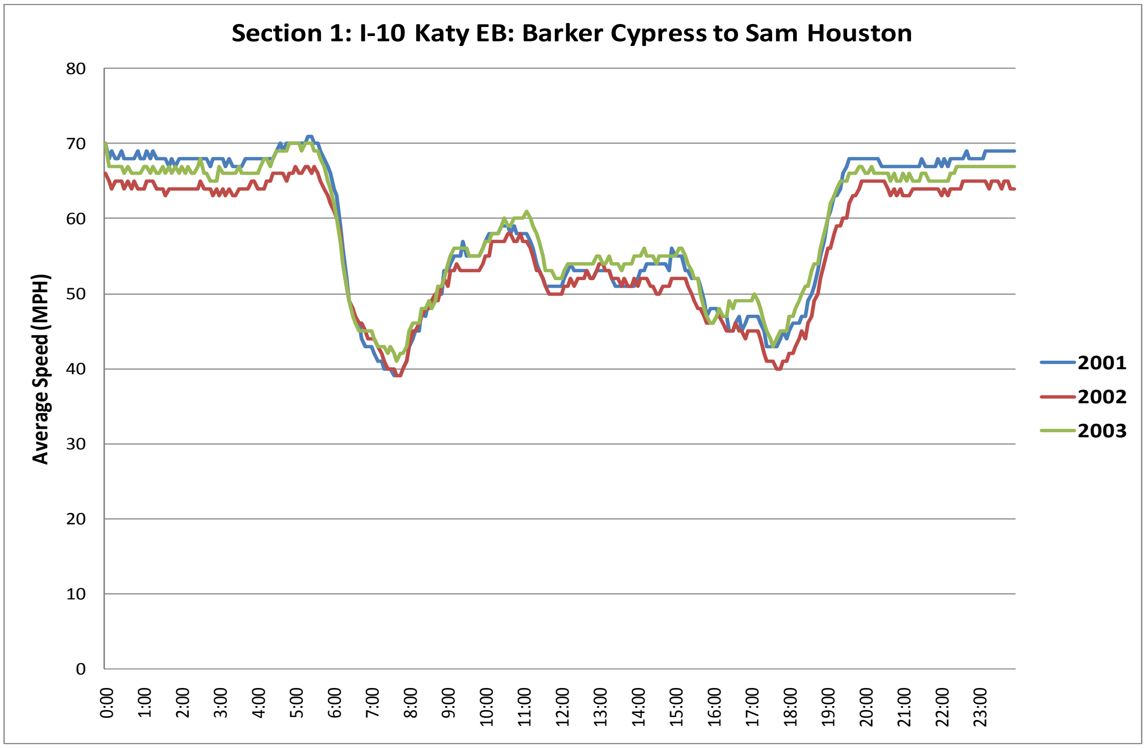


FIGURE 5.18 Average speeds of the three analysis periods for section 1.

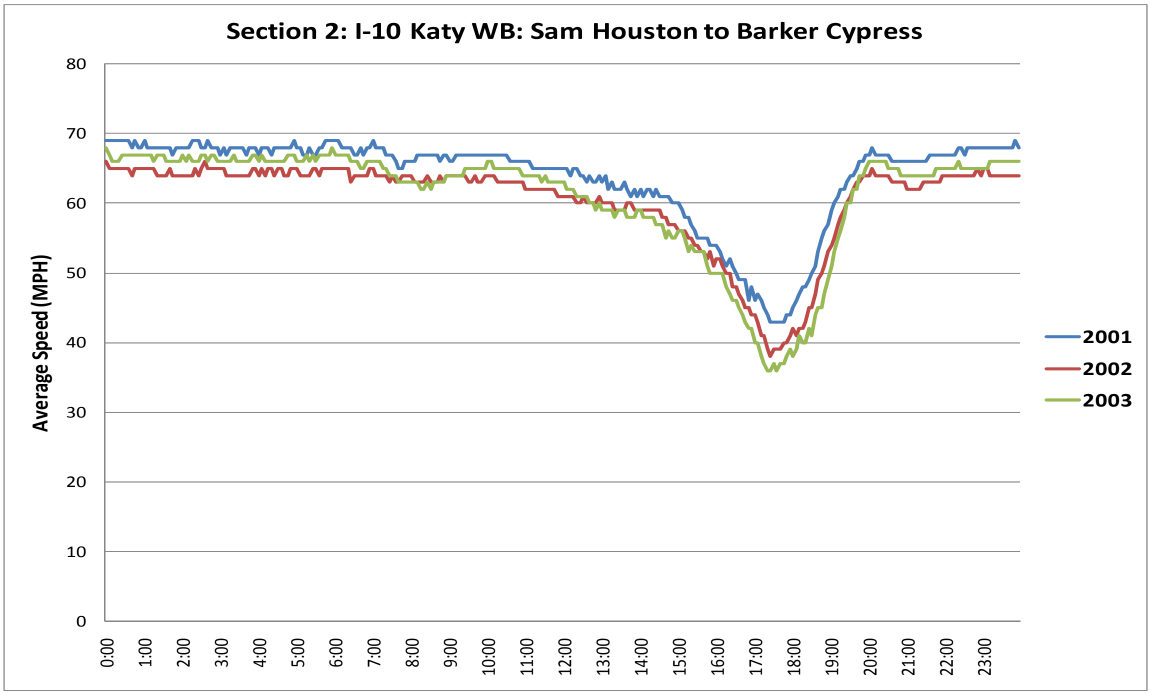


FIGURE 5.19 Average speeds of the three analysis periods for section 2.

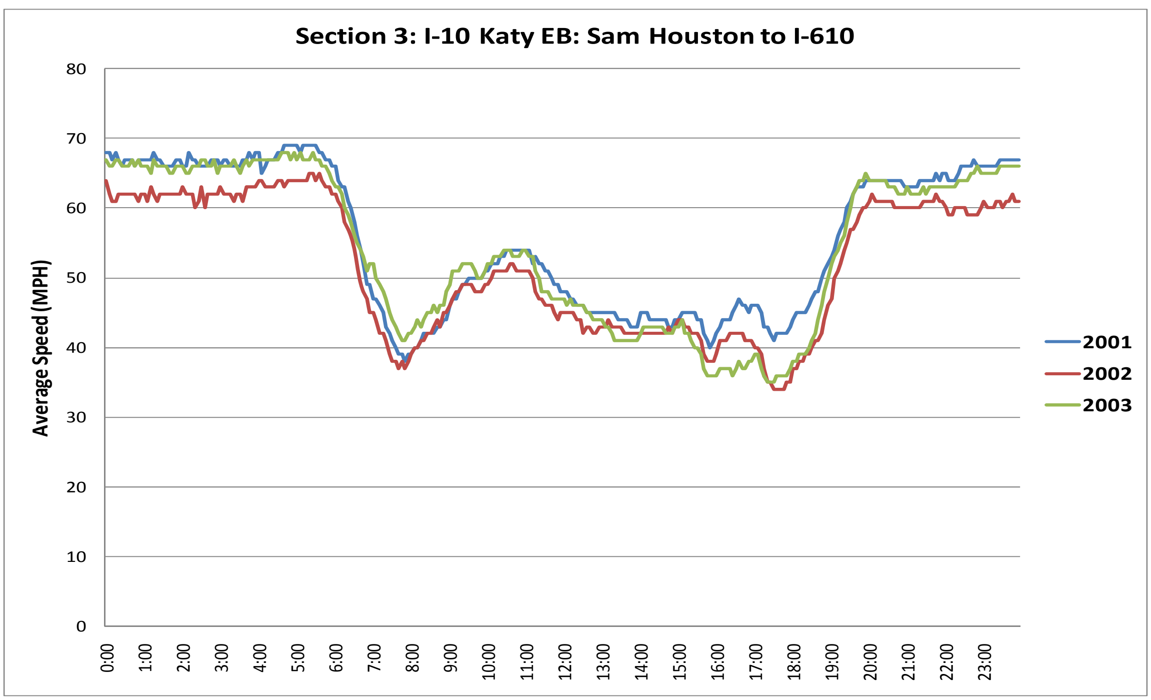


FIGURE 5.20 Average speeds of the three analysis periods for section 3.

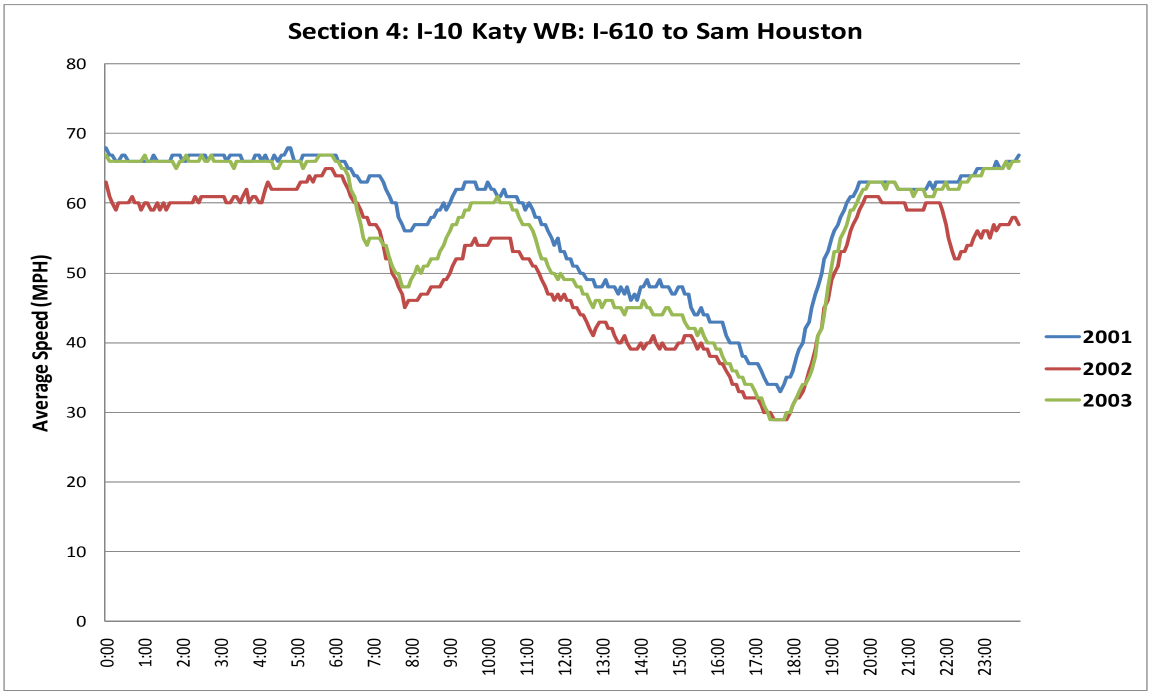


FIGURE 5.21 Average speeds of the three analysis periods for section 4.

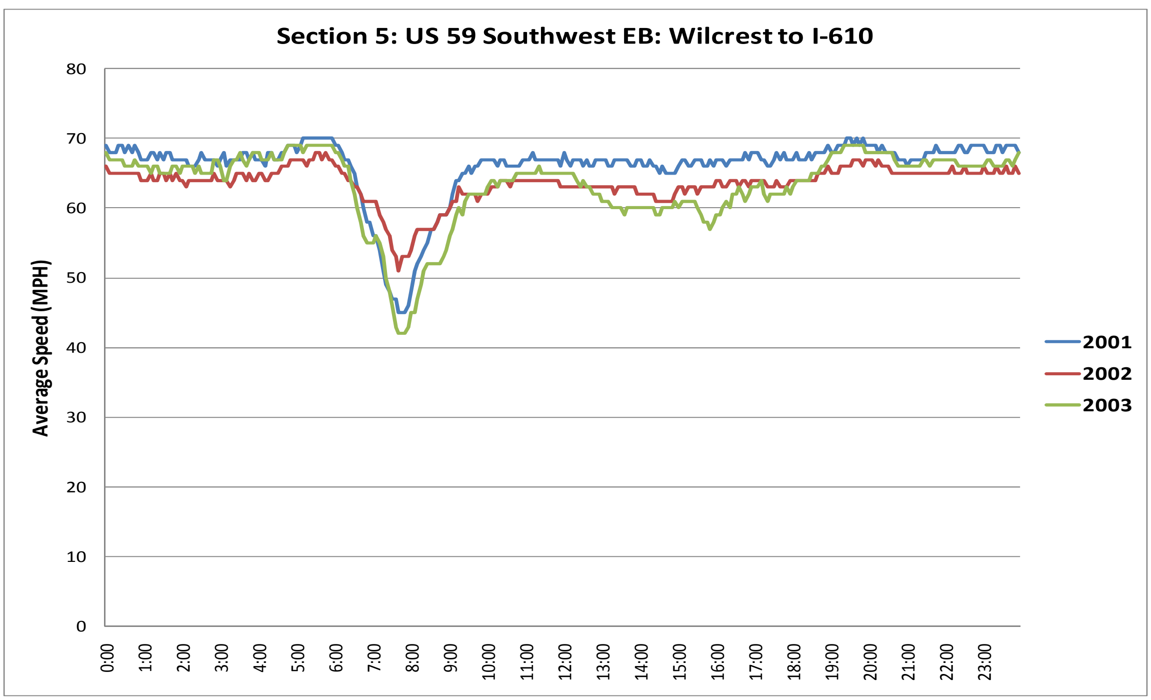


FIGURE 5.22 Average speeds of the three analysis periods for section 5.

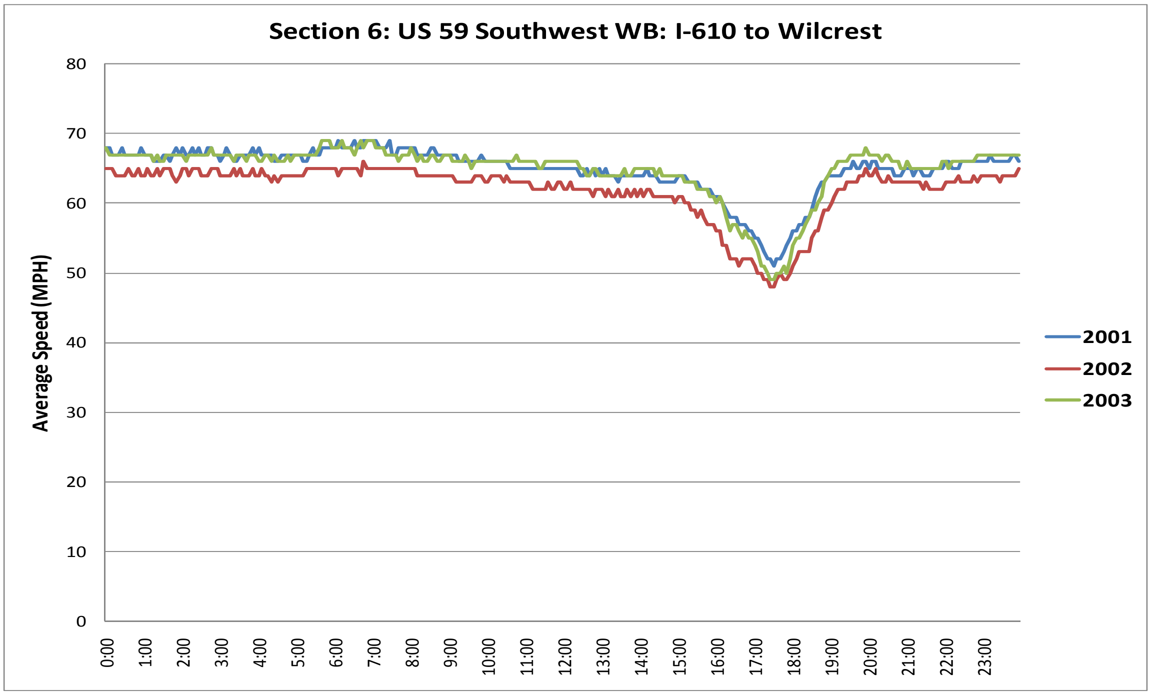


FIGURE 5.23 Average speeds of the three analysis periods for section 6.

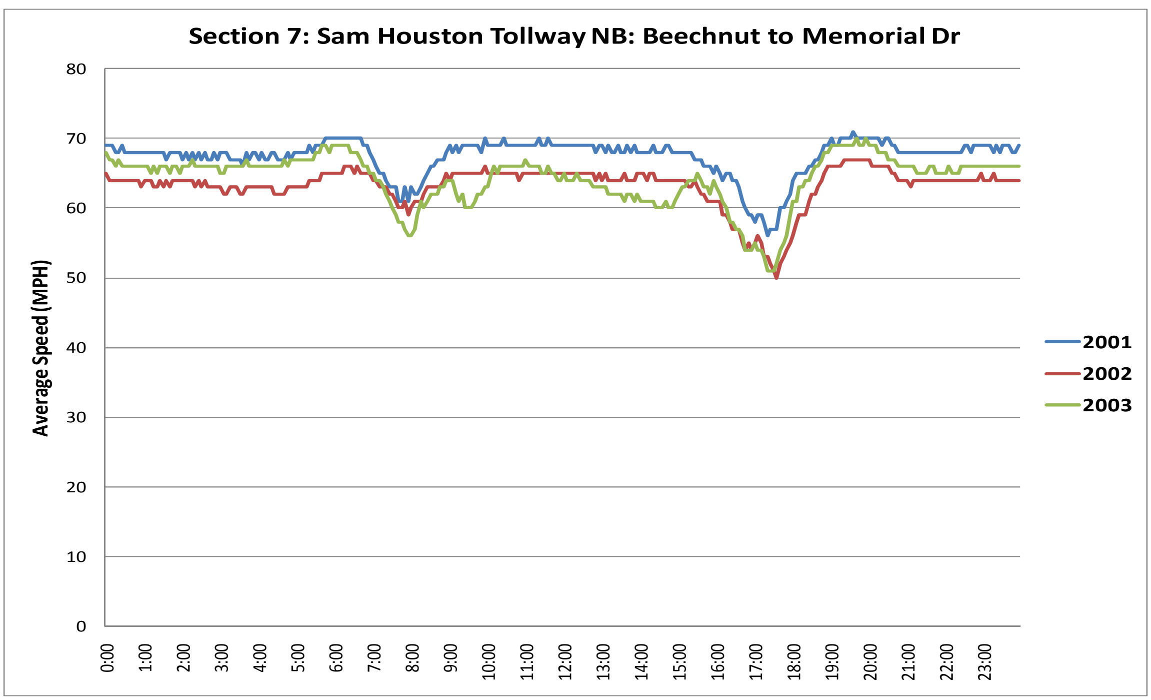


FIGURE 5.24 Average speeds of the three analysis periods for section 7.

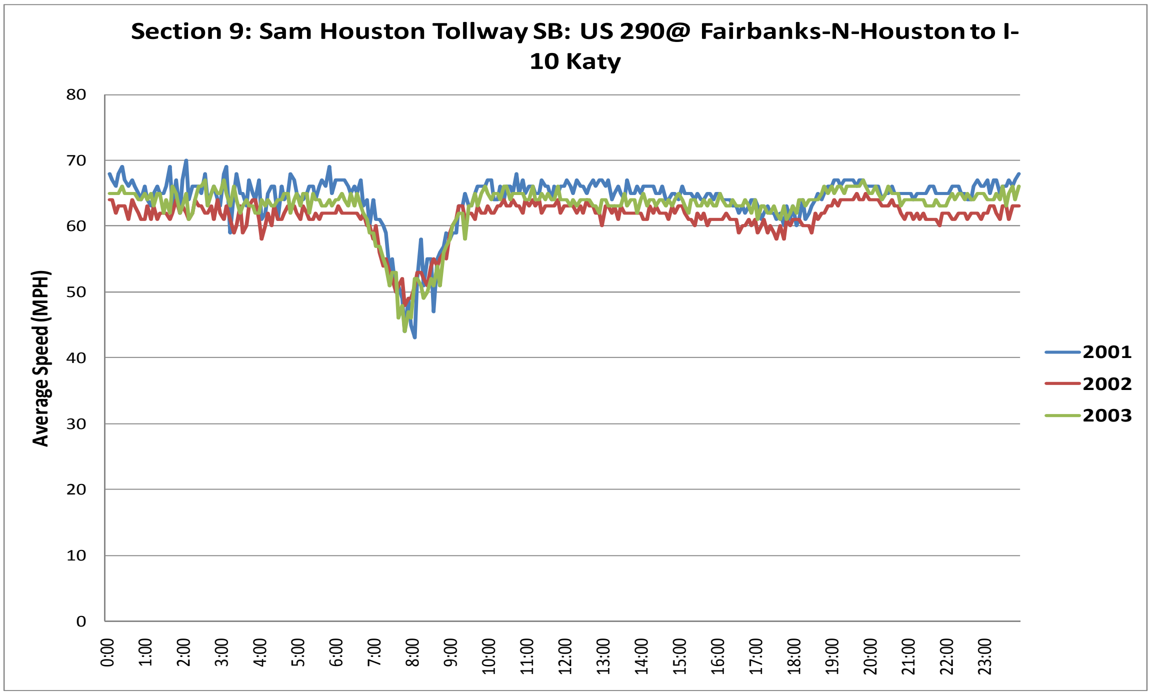


FIGURE 5.25 Average speeds of the three analysis periods for section 9.

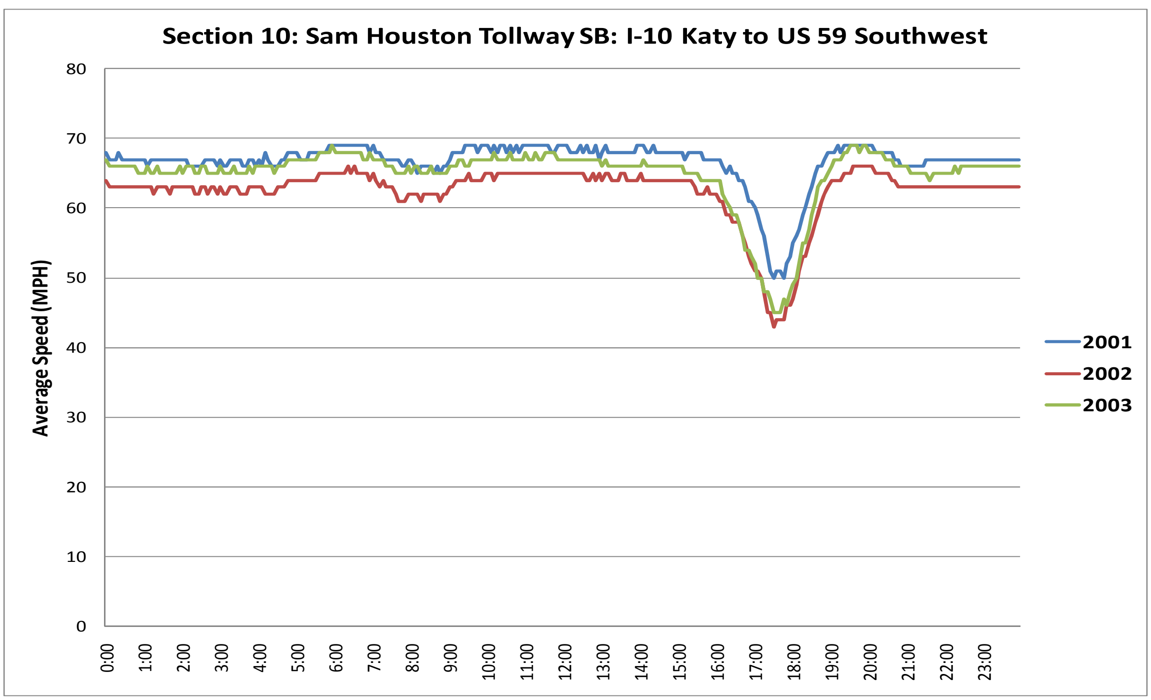


FIGURE 5.26 Average speeds of the three analysis periods for section 10.

5.3.2 Average Speed and AADT Trend for the Three Analysis Periods

The trends of both average speeds and AADT were examined and compared for the analysis periods.

5.3.2.1 *Trend of AADT*

The toll tag system collects the travel time directly but does not have volume data available. To obtain the travel growth of the analysis periods, Annual Average Daily Traffic (AADT) was used to examine the trend in travel growth. The disadvantage of AADT data is that it is bi-directional. Using AADT for exploring travel growth trend will not be able to differentiate the trends for the different directions of the same section of highway. The nine directional sections selected for the final study belong to six freeway sections. Six of the nine study sections were taken from three freeway sections with both directions included. The original data source for the AADT was from Texas Department of Transportation (TxDOT). The original AADT data were aggregated to match the study sections. Since Sam Houston Tollway is not maintained by TxDOT, the AADT data was not available for the three Sam Houston Tollway sections.

Table 5.5 lists the aggregated AADT for the six non-toll freeway sections and Table 5.6 lists the percentage change of AADT for the six sections. As presented in Table 5.5, the 2001 AADT was the lowest among the three years for all three sections. However, the 2002 and 2003 AADT showed different trends for different sections. One section had a 4% increase from 2002 to 2003. Another section had a 5% decrease from 2002 to 2003. Another section had virtually no change in AADT. The combined non-toll section AADT also showed the lowest AADT for 2001 and no change from 2002 to 2003.

TABLE 5.5 Aggregated AADT for the Three Analysis Years

Route & Section	Study Section Number	AADT		
		2003	2002	2001
I-10 Katy Barker Cypress to Sam Houston	1 & 2	175,029	167,757	147,320
I-10 Katy Sam Houston to I-610	3 & 4	184,920	195,135	164,492
US 59 Wilcrest to I-610	5 & 6	281,750	281,551	268,530
Total		641,699	644,443	580,343

TABLE 5.6 Percent Change of AADT for the Three Analysis Years

Route & Section	Study Section Number	Percent Change of AADT	
		2002 to 2003	2001 to 2002
I-10 Katy Barker Cypress to Sam Houston	1 & 2	4%	14%
I-10 Katy Sam Houston to I-610	3 & 4	-5%	19%
US 59 Wilcrest to I-610	5 & 6	0%	5%
Total		0%	11%

5.3.2.2 *Trend of off-peak period average speed*

The analysis below examined the average speeds and the trend of average speed for the off-peak period to test hypothesis 3 for the off-peak period. Hypothesis 3 is that the speed limit affects the travel time distribution for the free flow driving condition (i.e., the off-peak periods).

After observing the speed distributions for the study sections (as shown in Figures 5.18 through 5.26), the early morning and late night periods were used as the free flow driving condition. Both average speeds and the trend of average speeds were examined for the three analysis periods (from June to August in 2001, 2002 and 2003). Because the AADT data were not available for the toll way sections, combining the toll way and non-toll way sections may mix the effects. Therefore, the average speeds and trend of average speeds were analyzed by all sections for overall area-wide effect and also separately for non-toll and toll sections.

The off-peak average speeds of all sections, non-toll and toll sections for the three analysis periods are shown in Table 5.7. The average speed values for all section group combination confirmed the visual observation of the trend that the “before” period showed the highest average speeds; the “during “period showed the lowest speeds; and the average speeds for the “after” period were between the “before” and “during” periods. The trend of average speeds for the off-peak periods follows the trend of the speed limit for the analysis periods. The results also confirm that the differences of the off-peak average speeds among the three analysis periods were smaller than the posted speed limits differences. For example, the posted speed limit difference between the before and after periods is 5 mph. However, all results show that the actual speed difference in the study area was about 1 mph.

TABLE 5.7 Off-peak Average Speeds for the Three Analysis Periods

Section Groups	**Mean Speed of Analysis Periods (mph)**		
	Before (2001)	During (2002)	After (2003)
All Sections	66.61	62.76	65.63
Non-toll Sections	66.45	62.59	65.63
Toll Sections	66.93	63.12	65.63

The Analysis of Variance (ANOVA) test was performed to test whether the mean speeds for the three analysis periods are equal (as illustrated in Equation 3.11). Tables 5.8 through 5.10 list the results of the three ANOVA tests for all, non-toll, and toll sections, respectively. The *p*-values being less than 0.05 indicate that the mean of average speeds for the three analysis periods in the off-peak period was significantly different at the 95% confidence level.

TABLE 5.8 Off-Peak Period ANOVA Test Results for All Sections

Source	Degree of Freedom	Sum of Squares	Mean Square	F Statistics	*p*-value
Model	2	9477.03	4738.51	700.49	<.0001
Error	3558	24068.43	6.76		
Corrected Total	3560	33545.46			

TABLE 5.9 Off-Peak Period ANOVA Test Results for the Non-toll Sections

Source	Degree of Freedom	Sum of Squares	Mean Square	F Statistics	*p*-value
Model	2	6554.73	3277.36	372.20	<.0001
Error	2373	20895.47	8.80		
Corrected Total	2375	27450.21			

TABLE 5.10 Off-Peak Period ANOVA Test Results for the Toll Sections

Source	Degree of Freedom	Sum of Squares	Mean Square	F Statistics	*p*-value
Model	2	2969.29	1484.64	578.11	<.0001
Error	1182	3035.49	2.56		
Corrected Total	1184	6004.79			

The Tukey's Studentized Range tests were further performed to test the differences of average speeds in any two of the three analysis periods (as illustrated in Equation 3.12). Results (as shown in Tables 5.11 to 5.13) from three section groupings indicated that neither of the two analysis periods has similar average speeds for the off peak period.

TABLE 5.11 Off-peak Period Tukey's Test Results for All Sections

Tukey Grouping*	Mean	N	Year
A	66.61	1187	2001
B	65.63	1187	2003
C	62.76	1187	2002

* Means with the same letter are not significantly different.

TABLE 5.12 Off-Peak Period Tukey's Test Results for the Non-Toll Sections

Tukey Grouping*	Mean	N	Year
A	66.45	792	2001
B	65.63	792	2003
C	62.59	792	2002

* Means with the same letter are not significantly different.

TABLE 5.13 Off-Peak Period Tukey's Test Results for the Toll Sections

Tukey Grouping*	Mean	N	Year
A	66.93	395	2001
B	65.63	395	2003
C	63.12	395	2002

* Means with the same letter are not significantly different.

5.3.2.3 *Trend of peak period average speed*

Both average speeds and the trend of average speeds were examined for the three analysis periods. The trend of average speeds for the peak periods cannot be as easily identified visually as for the off peak periods. The ANOVA test as described in section 5.3.2.1 was performed to compare the difference of the average speed for the three analysis periods in peak travel period. The average speeds and trend of average speeds were analyzed for all sections, non-toll and toll sections separately to identify potentially different trends.

Due to the orientation of the selected freeway sections (e.g., inbound, outbound, or loops) and travel patterns in the Houston metropolitan area, most sections exhibited either a morning or evening peak congestion period. To study the effect of the speed limit change on speed distribution during the congested traffic condition, the congested traffic condition is defined as the time when the average speed equals to or is less than 50 mph in any of the three analysis period. There were 12 peak periods under the congested traffic conditions for the nine study sections.

The peak period average speeds of all sections, non-toll and toll sections for the three analysis periods are shown in Table 5.14. The average speeds for all section group combinations demonstrate a trend that the "before" period showed the highest average speeds; however, the average speeds for the “during “period and the “after” period were very similar. The trend of average speeds for the peak periods did not reveal the lowest speed occurred in the “during “period as was the trend for the off-peak periods.

TABLE 5.14 Peak Period Average Speeds for the Three Analysis Periods

Section Groups	**Mean Speed of Analysis Periods (mph)**		
	Before (2001)	During (2002)	After (2003)
All Sections	46.42	42.87	42.80
Non-toll Sections	43.40	40.26	40.16
Toll Sections	55.48	50.70	50.72

Tables 5.15 through 5.17 list the results of the ANOVA tests for the peak periods. Similar to the off peak, the results for the peak period showed that the mean of average speeds for the three analysis periods was different at the 95% confidence level.

TABLE 5.15 Peak Period ANOVA Test Results for All Sections

Source	**Degree of Freedom**	**Sum of Squares**	**Mean Square**	**F Statistics**	***p*-value**
Model	2	3701.53	1850.76	13.86	<.0001
Error	1293	172647.54	133.52		
Corrected Total	1295	176349.08			

TABLE 5.16 Peak Period ANOVA Test Results for the Non-toll Sections

Source	**Degree of Freedom**	**Sum of Squares**	**Mean Square**	**F Statistics**	***p*-value**
Model	2	2199.62	1099.81	9.19	0.0001
Error	969	115974.88	119.68		
Corrected Total	971	118174.51			

TABLE 5.17 Peak Period ANOVA Test Results for the Toll Sections

Source	**Degree of Freedom**	**Sum of Squares**	**Mean Square**	**F Statistics**	***p*-value**
Model	2	1636.98	818.49	9.73	<.0001
Error	321	26997.67	84.10		
Corrected Total	323	28634.65			

The Tukey's Studentized Range tests were also performed to test the differences of average speed in any two of the three analysis periods. Unlike the off peak period, the peak period results from three section groupings (Tables 5.18 to 5.20) showed that the average speeds for the during (2002) and the after (2003) analysis periods are not statistically different.

TABLE 5.18 Peak Period Tukey's Test Results for All Sections

Tukey Grouping*	**Mean**	**N**	**Year**
A	46.42	432	2001
B	42.87	432	2002
B	42.80	432	2003

* Means with the same letter are not significantly different.

TABLE 5.19 Peak Period Tukey's Test Results for the Non-toll Sections

Tukey Grouping*	**Mean**	**N**	**Year**
A	43.40	324	2001
B	40.26	324	2002
B	40.16	324	2003

* Means with the same letter are not significantly different.

TABLE 5.20 Peak Period Tukey's Test Results for the Toll Sections

Tukey Grouping*	**Mean**	**N**	**Year**
A	55.48	108	2001
B	50.72	108	2003
B	50.70	108	2002

* Means with the same letter are not significantly different.

5.3.2.4 *Trend of peak hour average speed*

To further study the effect of speed limit change on speed distribution during congested traffic condition, the difference of average speeds during the peak hour of the three-hour peak period was also tested. The purpose of using the peak hour average speeds for the same tests was to confirm the trends identified in the peak period data. Using the speeds only from the peak hour avoids including the free flow traffic condition if the congested driving conditions for some sections did not last 3 hours.

The peak hour was designated as morning peak hour (7:00 am to 8:00 am) or evening peak hour (5:00 pm to 6:00 pm) for the 12 identified peak periods. Therefore, there were 12 peak hours within the 12 peak periods for the nine study sections. To ensure that the designated peak hour had the worst traffic condition for each study section, the time of the lowest speed occurred for each section was checked. The lowest speeds for all sections were within the designated peak hour and were somewhere within the middle 20 minutes of the designated peak hour. It should be noted that for the designated peak hour to capture the worst hour for all three analysis periods may not be possible. This is because the time when the worst speed occurred changed during the three analysis periods. For example, the lowest speed for 2001 section 7 was from 17:20 to 17:25; the lowest speed for 2002 was from 17:35 to 17:40; and the lowest speed for 2003 was from 17:20 to 17:35.

The peak hour average speeds of all sections, non-toll and toll sections for the three analysis periods are shown in Table 5.21. The average speeds for all section group combinations demonstrate the same trend as the peak periods in that the “before” period showed the highest average speeds. The average speeds for the “during “period and the “after” period were very similar.

TABLE 5.21 Peak Hour Average Speeds for the Three Analysis Periods

Section Groups	**Mean Speed of Analysis Periods (mph)**		
	Before (2001)	During (2002)	After (2003)
All Sections	40.43	37.13	36.78
Non-toll Sections	37.74	35.01	34.75
Toll Sections	48.50	43.50	42.88

Tables 5.22 through 5.24 list the results of the ANOVA tests for the peak hour. Similar to the off peak and the peak period, the results for the peak hour showed that the mean of average speeds for the three analysis periods was significantly different at the 95% confidence level. Although for the non-toll sections, the mean of average speeds for the three analysis periods was very close.

TABLE 5.22 Peak Hour ANOVA Test Results for All Sections

Source	Degree of Freedom	Sum of Squares	Mean Square	F Statistics	*p*-value
Model	2	1168.87	584.43	6.14	0.0024
Error	429	40862.43	95.25		
Corrected Total	431	42031.30			

TABLE 5.23 Peak Hour ANOVA Test Results for the Non-toll Sections

Source	Degree of Freedom	Sum of Squares	Mean Square	F Statistics	*p*-value
Model	2	594.54	297.27	3.16	0.0436
Error	321	30158.86	93.95		
Corrected Total	323	30753.40			

TABLE 5.24 Peak Hour ANOVA Test Results for the Toll Sections

Source	Degree of Freedom	Sum of Squares	Mean Square	F Statistics	*p*-value
Model	2	683.76	341.88	9.33	0.0002
Error	105	3845.83	36.62		
Corrected Total	107	4529.59			

The Tukey's Studentized Range tests were also performed for the peak hour. Similar to the peak period, results (as shown in Tables 5.25 – 5.27) from three section groupings showed that the average speeds for the during (2002) and the after (2003) analysis periods are not statistically different for the peak hour.

TABLE 5.25 Peak Hour Tukey's Test Results for All Sections

Tukey Grouping*	Mean	N	Year
A	40.43	144	2001
B	37.13	144	2002
B	36.78	144	2003

* Means with the same letter are not significantly different.

TABLE 5.26 Peak Hour Tukey's Test Results for the Non-toll Sections

Tukey Grouping*	**Mean**	**N**	**Year**
A	37.74	108	2001
A	35.01	108	2002
A	34.75	108	2003

* Means with the same letter are not significantly different.

TABLE 5.27 Peak Hour Tukey's Test Results for the Toll Sections

Tukey Grouping*	**Mean**	**N**	**Year**
A	48.50	36	2001
B	43.50	36	2002
B	42.88	36	2003

* Means with the same letter are not significantly different.

5.3.3 Comparing the Trends of the Off-peak, Peak Period, and Peak Hour

Using the average speeds listed in Tables 5.7, 5.14 and 5.21, the trend of average speeds can be plotted for the three section group combinations (as shown in Figure 5.27). The three section group combinations demonstrate the same trend of average speeds for the off-peak, peak period, and peak hour.

For the off-peak periods, lowering speed limit to 55 mph in 2002 had an effect on the average speed. However, the actual free flow speed was higher than 55 mph for all sections. In addition, actual speed difference between the "after" and "before" periods was smaller than the 5 mph speed limit difference.

For the peak periods, the assumption is that higher AADT would result in higher peak period volume which may in turn cause lower peak period speed and vice visa. This assumption can be illustrated by the speed and flow relationship in the traffic flow theory (Figure 5.28). The approximate areas where the average speeds of the off-peak, peak period, peak hour and the worst 15 minutes of the day fall in the speed flow diagram are illustrated in Figure 5.28. According to the traffic flow theory, speed decreases as the flow level increases up to the maximum flow under free flow conditions.

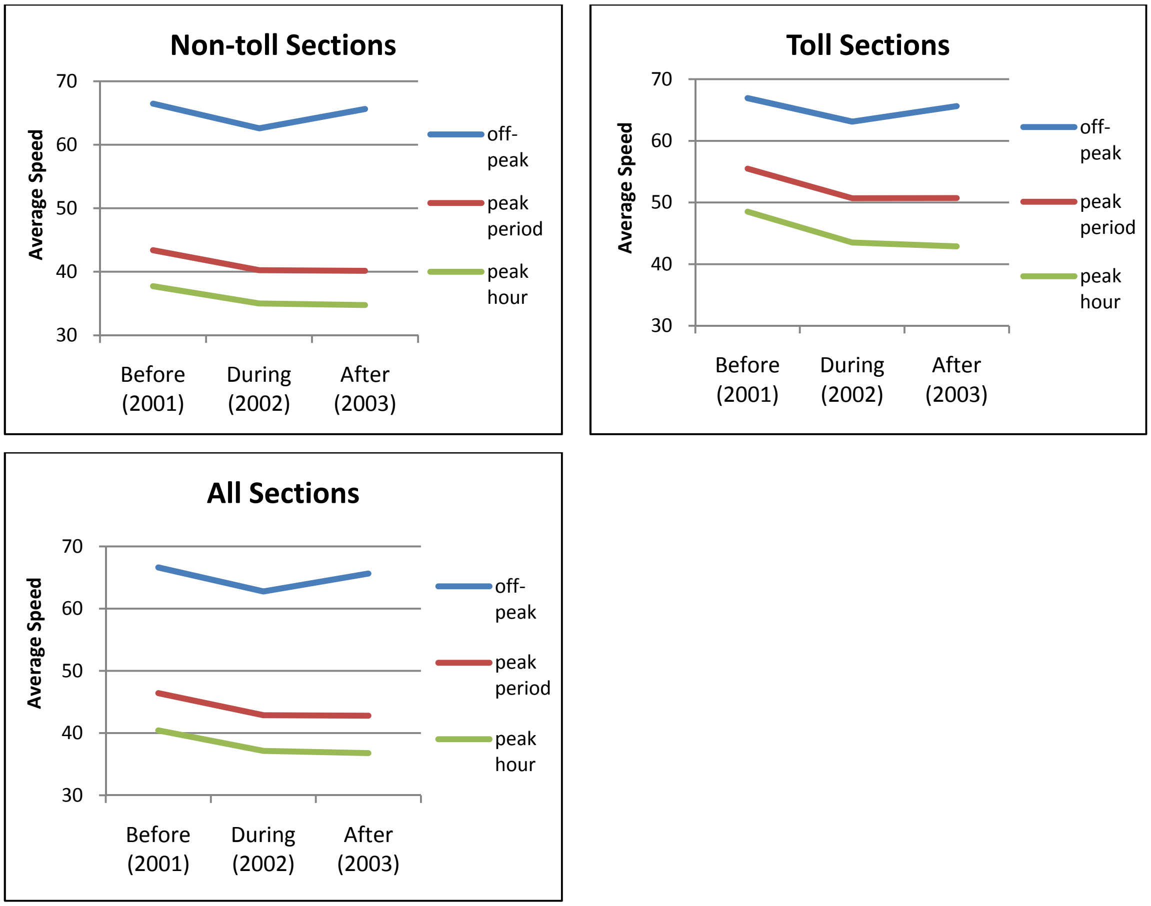


FIGURE 5.27 Trends of average speed for off-peak, peak period and peak hour.

Under this assumption for peak period, one would expect that the peak period average speeds for 2001 were the highest and the peak period speeds for the 2002 and 2003 periods were about the same (as shown in Figure 5.29). The ANOVA results from both peak period and peak hour confirmed the trend based on the assumption. The results from peak period and peak hour may suggest that volume is the dominant factor for speed distribution in the forced-flow conditions.

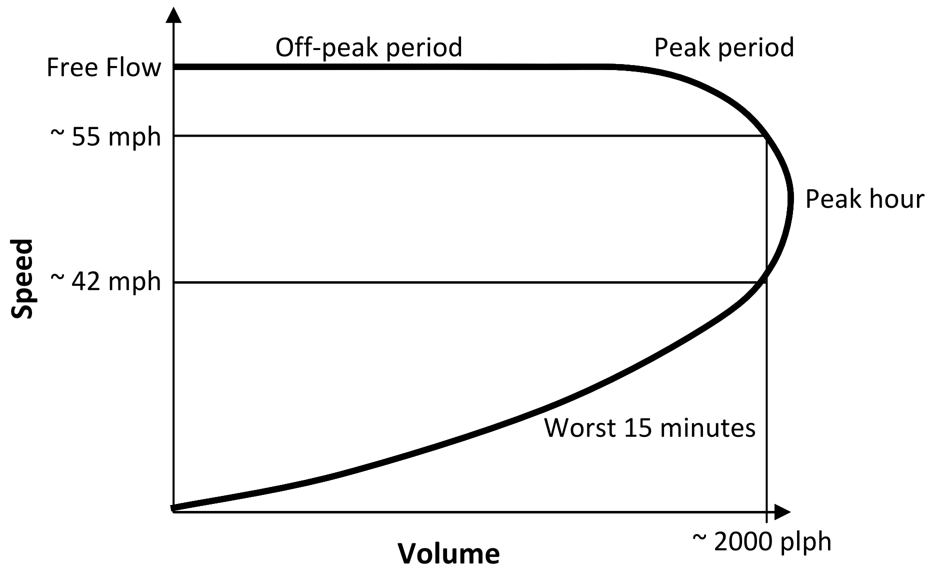


FIGURE 5.28 Speed and flow diagram for the peak period average speeds.

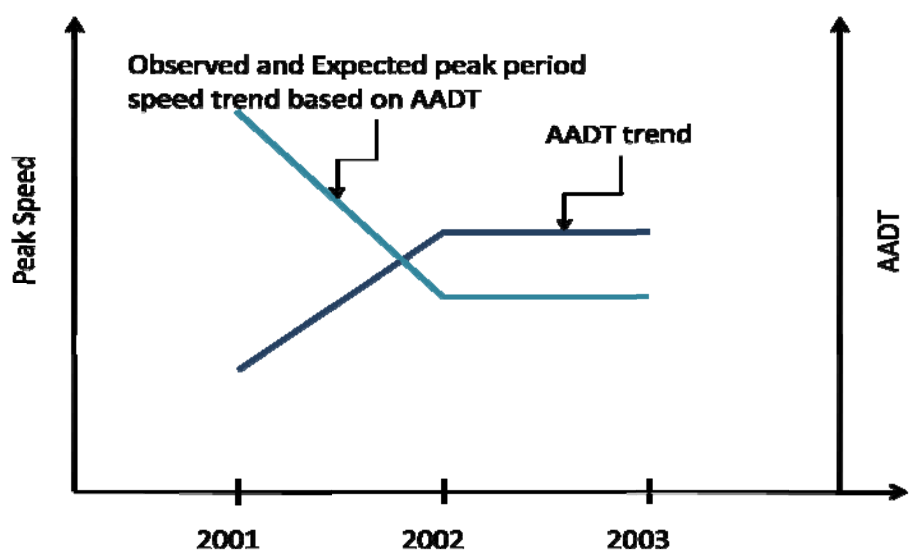


FIGURE 5.29 Observed and expected peak period speed trend for the analysis periods.

5.3.4 Identifying Confounding Factors

Several confounding factors other than lowering speed limit could have attributed to the lower average speed in 2002 for the off peak period. However, none of these factors were believed to be significant to affect the average speed in the off peak period. These confounding factors are discussed below.

- An abnormal increase of incidents in the 55 mph speed limit effective month of 2002 might have been the cause of the lower speed. However, the likelihood of this confounding factor was discounted by observing that the 2002 off peak period speed was the worst among the three analysis periods in all study sections. The likelihood of all sections having increased incidents is small.
- Any severe weather events in the three months of 2002 might have caused a bad road condition, which in turn caused the lower speed. Severe weather conditions such as a tropical storm occurring in the Houston area in the summer times could cause bad driving conditions and longer travel time. However, according to the National Oceanic and Atmospheric Administration, no tropical storm landed in the Gulf region in 2002.
- Any major road construction in the region might have caused delays and slowed the travel. According to TxDOT, no major construction happened in the study section in 2002. However, the Katy Freeway Reconstruction Program (*42*) started in summer 2003. The road section that started in May 2003 had an overlap with the study section 1 and 2. This might be the explanation of the lower peak period speed for section 2 in the 2003 (as seen in Figure 5.19).

5.3.5 Speed Limit Change and Speed Distribution

Posted speed limit is the reference speed for driving at the free flow traffic condition. The results from the off-peak speed show that lowering speed limit did have an effect on the off-peak speed distribution. However, the magnitude of the effect may not be as significant as the differences of posted speed limit values.

For the peak period and the most congested driving hour, the speed limit change did not have an effect on the speed distribution. However, the speed distribution followed the reverse direction of the volume. It is believed that during forced-flow conditions volume is the dominant factor for speed distribution.

When the speed limit is used as the free flow speed or a percentage of the speed limit [which is the current practice for many MPOs (*28*)] is used as the "target" or acceptable speed to estimate the congestion, the amount of congestion may be underestimated because the actual free flow speed is higher than the speed limit. For the case of this study, during the 55 mph speed limit effective period, if 80% of the speed limit was used as the "target" speed, the "target" speed would be 44 mph. However, the actual free flow speed was about 65 mph for some study sections. 44 mph is only about 67% of the 65 mph free flow speed.

CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS

This chapter summaries the conclusions of the three research questions. The limitations of each research method are also discussed. Future research questions are also recommended.

6.1 Conclusions

Each of the three research questions is reiterated and followed by the conclusions. The limitations of the research method for each research question are also discussed.

Research question 1. Do rankings of congestion measures for freeway segments hold steady across different congestion thresholds? Are there situations where a change in threshold value would change the congestion ranking of freeways?

The rankings of congestion measures for freeway segments hold steady across the congestion threshold speeds ranging from 60 mph to 30 mph and across the congestion measures that include delay per mile, Travel Time Index (TTI) and Planning Time Index (PTI). Not surprisingly, the closer the congestion threshold speeds used, the closer the rankings are. The rankings for the most and the least congested freeway segments are fairly robust across the threshold speeds. In other words, the most congested freeway segments under the 60 mph threshold speed remain the most congested segments when evaluated under the 35 mph threshold speeds. Therefore, from an investment point of view, the congestion threshold speed used is not a concern for funding allocation.

Two limitations exist in the research method. First, although study sections were selected to cover the range of factors believed to influence travel time distribution, the sample size for a specific range of a factor may be limited. For example, out of the 147 freeway segments used for the study, 13 of them were in the area type of Central Business District (CBD). Although the proportion may reflect the real freeway mileage for this area type, the sample size for CBD may not be large enough to draw any conclusions on findings specifically for the CBD area type. Since the concern of the study is for all area types, this limitation is believed to have a minimal effect on the overall findings. Second, although data of one entire year were used to minimize the possibility of confounding factors (e.g., seasonality), some confounding factors may exist in some sections' data. For example, some sections may have experienced major construction work for the most part of the analysis year while other sections may have adverse weather conditions for some part of the year. These confounding factors were not specifically examined because the sample size is believed large enough to offset the effects of confounding factors in regards to the specific research hypothesis being examined.

Research question 2. What is the relationship between delay and congestion threshold? As the congestion threshold is changed, how does delay change? Is the relationship linear?

The relationship between the delay values from an alternative threshold and the 60 mph threshold has a quadratic form. As the alternative threshold decreases further away from 60 mph, the increment is larger. The more congested a section is, the less the threshold affects measured congestion. For very congested sections, most of the delay is associated with speeds below 30 mph.

The sample size for determining parameters of the quadratic relationship may be limited. The regression quadratic function may change if more samples are added. Because the overall relationship is the primary concern of the study, the sample size is believed large enough for estimating an overall relationship between delay and congestion threshold speeds.

Research question 3. Is speed limit one of the factors that affect travel time distribution? How speed limit should be used as the congestion threshold?

The study shows that the posted speed limit is one of the factors affecting travel time distribution in the off-peak or any free flow driving condition period. In contrast, speed limit has no effect on travel time distribution during congested driving conditions. The speed limit may seem like a good candidate for the congestion threshold; however, the actual free flow driving speed is higher than the posted speed limit. If the speed limit as the free flow speed or a percentage of speed limit as the “target” or acceptable speed was used to estimate the congestion, the amount of congestion might be underestimated.

Two limitations exist in the research method. First, no directional volume or AADT data were available for a comparison with the directional peak period average speed data. The directional AADT growth may have a different trend from the bi-directional AADT. In this study, the speed trend for some sections (directional) was different from the overall sections. The availability of directional AADT data would further justify the findings. Second, the study sections were chosen from one precinct of the Harris County to avoid the confounding factor of different law enforcement practices on speed. However, for an area wide study, sections from other precincts could have been included to verify the overall trend.

6.2 Policy Implications

Although the question of “When does congestion start?” may be debated among researchers and practitioners for a long time, the effect of the congestion thresholds on congestion measures appears to be minimal when selecting the most congested sections. The values of the measures will change, and these changes affect some of the investment decision-making for transportation projects, but in most cases the relative changes are small.

The findings of this research should help areas that are struggling with definitions of the proper threshold for evaluating transportation projects. The research indicated that the same set of the projects will be chosen whether 60 mph or 35 mph was used as the beginning of congestion. However, within the chosen set of the projects, the cost effectiveness of each project can be further investigated for investment decisions.

The relationship of delay under different thresholds can be used to compare the magnitude of congestion for freeways/corridors/areas that were evaluated with different congestion thresholds. In addition, this relationship can also be used to predict or compare the amount of congestion from a different congestion threshold if a specific threshold is required for decision making.

While the posted speed limit or a percentage of the posted speed limit may seem like a good candidate for a congestion threshold, in reality the amount of congestion can be severely underestimated depending on the driving culture of an area. The findings of this research indicate that a change in the speed limit does not affect speed distribution during forced-flow conditions. Lowering the speed limit may not help ease congestion, although it will reduce speeds in the off-peak periods.

6.3 Recommended Future Research

The findings of this research provide a starting point for the research on congestion threshold. Although the major findings of the research are believed to be generalizable to other freeways, further research can provide a more complete picture of the congestion threshold impacts. The topics for the future research are listed below.

- Regional patterns seem to exist in travel time distributions. For example, the travel time distributions for the study sections in the Los Angeles area seem to have a “flatter top” and the study sections in Minneapolis-St. Paul area seem to have a more “pointed top.” Does corridor or regional land use have an effect on the pattern of travel time distribution? Is it more appropriate to have a nationwide standardized congestion threshold or a regionally tailored threshold using the travel time distributions as the basis?
- Although Houston, San Francisco, and Philadelphia metropolitan areas have similar population (between 3 to 7 million), freeway sections from Houston seem more congested than the other two. The 2006 travel rates of selected freeway sections in Philadelphia area had an average speed higher than 30 mph for the

entire peak periods of an average work day. The relatively high speed in the peak periods is not often seen on the freeway sections in a metropolitan area of its size. About half of the selected freeway sections in the Philadelphia area were on I-95. Does the congestion management program along the I-95 corridor have an effect on the higher speed in the peak period? Or does any land use factor play a role on the more congested sections in Houston and less congested sections in Philadelphia?

- For the sections ranked outside of the prediction limits, what are the common characteristics of these sections? What characteristics made the rankings of these sections significantly different? According to the findings, there are more sections that were ranked much lower when using alternative threshold speeds compared to the baseline threshold speed. Or in terms of travel time distribution, there are more “wide flat top”’ distributions than the “narrow pointed top” distributions. Is this simply the randomness of the selection set or do the findings apply to other sections as well?
- Although a before and after study approach was used for the effect of speed limit on travel time distribution, a cross-sectional approach can also be used to study the effect. Study sections from different metropolitan areas across the nation would give more perspective on the role of speed limit in travel time distribution.
- Similar research can be conducted on arterials. Compared to freeways, the speeds on arterials are much lower. In addition, the same speed differences as on the freeways would mean much longer travel time differences for arterials. There are few fixed sensors on arterials in the U.S. With the growing interest of collecting traffic data through the probe vehicle technique, data issues for similar research on arterials can be overcome.

REFERENCES

1. Freeman, P. *A Decade of Action in Transport: An Evaluation of World Bank Assistance to the Transport Sector, 1995-2005*. The World Bank, Washington, D.C., 2007.
2. Schrank, D., and T. Lomax. *The 2009 Urban Mobility Report*. Texas Transportation Institute, College Station, TX, 2009.
3. *The National Household Travel Survey* (NHTS), Report by the Office of Information, Federal Highway Administration, Washington, D.C., 2001.
4. Pisarski, A. E. *Commuting In America III*, Transportation Research Board, Washington, D.C., 2006.
5. Turner, T., Margiotta, R., and T. Lomax. *Monitoring Urban Freeways in 2003: Current Conditions and Trends from Archived Operations Data*, Report No. FHWA-HOP-05-018, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2004.
6. *1998 California Transportation Plan: Transportation System Performance Measures*, Final Report, California Department of Transportation, Sacramento, August 1998.
7. Florida's Mobility Performance Measures Program, Transportation Statistics Office, Office of the State Transportation Planner, Florida Department of Transportation, Tallahassee, 8 pp. www.dot.state.fl.us/planning/statistics/mobilitymeasures/mmpresentation.pdf. Accessed March 21, 2010.
8. *Maryland Highway System Performance Report*, Presented at the Transportation Research Board Peer Exchange Meeting on Performance Measures, Madison, Wisconsin, August 2000.
9. Pickrell, S., and L. Neumann. *Use of Performance Measures in Transportation Decision Making. In Performance Measures to Improve Transportation Systems*

and Agency Operations: Report of a Conference, Irvine, California, 2000, pp. 17-33.

10. Downs, A. *Still Stuck in Traffic*. The Brookings Institution, Washington, D.C., 2004.
11. *The Spread of Congestion in Europe*, Conclusions of Round Table 110, European Conference of Ministers of Transport, Paris, 1998.
12. Levinson, H. S., R. H. Pratt, P. N. Bay, G. B. Douglas. *Quantifying Congestion*. Interim Report. Transportation Research Board, National Research Council, Washington, D.C., 1992.
13. *Highway Capacity Manual*, Transportation Research Board, National Research Council, Washington, D.C., 2000.
14. Lomax, T., S. Turner, and G. Shunk. *Quantifying Congestion*, National Cooperative Highway Research Program Project report 398, National Academy Press, Washington D.C., 1997.
15. Bertini, R. *You Are the Traffic Jam: An Examination of Congestion Measures.* Preprint CD-ROM, 85th Transportation Research Board Annual Meeting of the Transportation Research Board, Washington, D.C., January 2006.
16. Margiotta, R., T. Lomax, M. Hallenbeck, S. Turner, A. Skabardonis, C. Ferrell, and B. Eisele. *Guide to Effective Freeway Performance Measurement*. National Cooperative Highway Research Program Project 3-68, National Research Council. February, 2007.
17. Colman, S. B. *Predicting the Duration of Congestion on Bay Area Freeways*. Dowling Associates, Inc. March 26, 2007. www.dowlinginc.com/pdf/Congestion%20Duration%20Paper.pdf. Accessed March 21, 2010.
18. *Question of the Month: What Should Be Our Common Definition of "Congestion?"* National Transportation Operations Coalition (NTOC). www.ntoctalks.com/itsforum/index.cgi?noframes;read=1347. Accessed March 21, 2010.

19. Arnold, E. D., Jr. *Congestion on Virginia's Urban Highways*. Report No. FHWA/VA-88/24, Virginia Transportation Research Council, Charlottesville, Virginia, April 1988.

20. Turner, S., R. Margiotta, and T. Lomax. *Lessons Learned: Monitoring Highway Congestion and Reliability Using Archived Traffic Detector Data*, FHWA-HOP-05-003, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2004.

21. Kreis, D., B. Howell, and L. O'Connell. *Statewide Planning Scenario Synthesis: Transportation Congestion Measurement and Management*. Research Report KTC-05-32/SPR303-05-IF, Kentucky Transportation Center. The University of Kentucky, 2005.

22. *A Guidebook for Performance-Based Transportation Planning.* Cambridge Systematics, Inc. National Cooperative Highway Research Program Project *Report 446:* Transportation Research Board, National Research Council, Washington, D.C., 2000.

23. *National Transportation Operations Coalition (NTOC) Performance Measures Initiative – Final Report*, July 2005. www.ntoctalks.com/ntoc/ntoc_final_report.pdf. Accessed March 21, 2010.

24. The Cost of Urban Congestion in Canada, Transport Canada, Environmental Affairs, March 22, 2006. www.gatewaycouncil.ca/downloads2/Cost_of_Congestion_TC.pdf. Accessed March 21, 2010.

25. *Metropolitan Freeway System 2008 Congestion Report*. Minnesota Department of Transportation, Metro District Office of Operations and Maintenance, Regional Transportation Management Center, March 2009.

26. *Year 2002 Bay Area Freeway Congestion Data*. California Department of Transportation, District 4, Office of Highway Operations. www.mtc.ca.gov/library/state_of_the_system/d4hicomp2002.pdf. Accessed March 21, 2010.

27. *Mobility in the Boston Region, Existing Conditions and Next Steps, the 2004 Congestion Management System Report*, Boston Region Metropolitan Planning Organization, December 2004. www.ctps.org/bostonmpo/4_resources/1_reports/1_studies/2_highway/2004_cms.html. Accessed March 21, 2010.

28. *Congestion Management Process (CMP)*, Nashville Area Metropolitan Planning Organization, Amended September 19, 2007. http://www.nashvillempo.org/docs/NAMPO_CMP_Amend091907.pdf. Accessed March 21, 2010.

29. *The 2009 Congestion Report.* Washington State Department of Transportation, November 2009. www.wsdot.wa.gov/NR/rdonlyres/2F00DBB2-44F9-43FA-8D77-5D25FBE50AFE/0/2009_Congestion_Report.pdf. Accessed March 21, 2010.

30. Laetz, T. J. Predictions and Perceptions, Defining the Traffic Congestion Problem. *Technological Forecasting and Social Change* Vol. 38, No. 3, 1990, pp. 287-292.

31. *The Keys to Estimating Mobility in Urban Areas: Applying Definitions and Measures that Everyone Understands*. A White Paper Prepared for the Urban Transportation Performance Measure Study, Texas Transportation Institute, 2005.

32. Boyce, D. B., J. Hicks, and A. Sen. In-Vehicle Navigation Requirements for Monitoring Link Travel Times in a Dynamic Route Guidance System. *ADVANCE Working Paper Series, Number 2*. Urban Transportation Center, University of Illinois at Chicago. Chicago, Illinois, March 1991.

33. *Travel Time Data Collection Handbook*, Report No. FHWA-PL-98-035, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1998.

34. Fujito, I., R. Margiotta, W. Huang, and W. A. Perez. *Effect of Sensor Spacing on Performance Measure Calculations.* Transportation Research Record: Journal of the Transportation Research Board, Vol. 1945, 2006, pp. 1-11.

35. Smith, B. L., R. B. Holt, and B. Park. *Travel Time Estimation for Urban Freeway Performance Measurement: Understanding and Improving Upon the Extrapolation Method*, Preprint CD-ROM, 83rd Transportation Research Board Annual Meeting, 2004.
36. Smith, B. L., and M. D. Fontaine. *Private-Sector Provision of Congestion Data*. NCHRP 70-01 Final Report, National Cooperative Highway Research Program, February 2007.
37. Young, S. E., *I-95 Corridor Coalition Probe Vehicle Project Validation Traveler Information Services Program.* Track Committee Meeting, September 23, 2008.
38. Cook, T. D., and D.T. Campbell. *Quasi-Experimentation*, *Design and Analysis Issues for Field Settings.* Houghton Mifflin Company, Boston, Massachusetts, 1979.
39. Campbell, D. T., and J. C. Stanley. *Experimental and Quasi-experimental Designs for Research.* Rand McNally, Chicago, 1966.
40. Margiotta, R., H. Cohen, R. Morris, J. Trombly, and A. Dixson. *Roadway Usage Patterns: Urban Case Studies.* Science Applications International Corporation and Cambridge Systematics Incorporated, June 1994.
41. Montgomery, D., and G. Runger. *Applied Statistics and Probability for Engineers.* Second Edition. John Wiley & Sons, Inc. New York, Chichester, Brisbane, Toronto, Singapore, 1999.
42. Katy Freeway Homepage. Texas Department of Transportation. katyfreeway.org/contracts.html. Accessed March 21, 2010.

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