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DEVELOPMENT AND TESTING OF A FREEWAY RECURRING CONGESTION MEASURE

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ABSTRACT

DEVELOPMENT AND TESTING OF A FREEWAY RECURRING CONGESTION MEASURE

By

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Selecting the most appropriate measure for evaluating Advanced Traffic Management Systems (ATMS) is vital in detecting the true impact of this technology. This study developed a freeway recurring congestion measure that is sensitive to short term fluctuations in traffic speed and can be used in evaluating ATMS systems. The measure quantifies recurring congestion on a location, segment, or system basis. The analysis used data from detectors in a freeway system in the Detroit, Michigan metropolitan area. Models were developed to predict start time and duration of recurring congestion, and values were assigned to congestion on each of the study segments. The study recommends a sampling plan for measurements over space, weekdays, seasons, and the data collection frequency to quantify congestion. A sensitivity analysis was performed to compare the developed measure with an existing recurring congestion measure, and to determine the ratio of recurring and non-recurring congestion. Future research topics were also recommended.

Dedicated to my wife Bushra,

and my sons Omar and Osama

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INTRODUCTION

1.1 Overview

Traffic congestion is recognized as a major problem in urban areas with significant effects on the economy, travel behavior, and land use. Although traffic congestion is not a new problem for the central city, it has spread to cover suburban areas. Schrank and Lomax (1997) estimated that the annual cost of congestion in 50 urban areas in 1994 exceeded $53 billion. They also estimated that 90 percent of total congestion costs in major urban area are attributed to travel delay, with the other 10 percent attributed to fuel cost.

The decline in urban mobility resulting from congestion has become a major concern to the transportation and business community and to the public. Measuring congestion assists the transportation professionals and policy makers in communicating problems, developing transportation system improvement strategies, and formulating new policies and programs.

Several methods, based on travel time and delay, have been used for measuring congestion. Despite the importance of these methods, there is no generally accepted congestion measure for use by public agencies. Moreover, current methods neither produce comparable results for various systems with similar congestion conditions nor are they appropriate for evaluating the effect of Intelligent Transportation Systems applications such as traffic management systems. There is a need for a new congestion measure that accounts for small variations in traffic speed and can be used in evaluating traffic management systems.

A review of the literature on the definition, measurement, and methods to alleviate congestion, are presented in the following subsections.

1.1.1 Congestion Definition and Characteristics

Traffic congestion reflects an increase in delay or travel time beyond a threshold acceptable to users. This threshold may vary by type of transportation facility, geographic location, and time of day (Lomax, Turner, and Shunk, 1997). For example, freeway congestion usually results when the road system is unable to accommodate traffic at an acceptable speed and extends over both space and time (Turner, Lomax, and Levinson, 1996).

Congestion can be divided into two major categories based on its occurrence predictability:

a. Recurring congestion usually occurs at a predictable location during specific periods of the day due to normally heavy traffic during these periods (e.g. during peak commute periods).

b. Nonrecurring congestion takes place when an incident or special event results in lane closure, increased demand, and/or reduced capacity.

The magnitude and duration of the nonrecurring congestion is difficult to quantify because of limited information on incidents. Although many methodologies have been developed to identify incidents, no one has been able to indicate a clear differentiation between recurring and nonrecurring congestion. As a result, recurring congestion databases partially still include congestion due to incidents.

The current practice of some transportation agencies, for example the California Department of Transportation (CALTRANS), assumes that congestion is divided equally into recurring and nonrecurring congestion (Epps, Cheng, and May, 1994). Lindley (1986) reported that nonrecurring congestion accounted for more than 61 percent of all urban congestion in 1984. He proposed a model to measure recurring and nonrecurring congestion based on the Federal Highway Administration (FHWA) Highway Performance Monitoring System (HPMS) database. His model estimates an average split of 33 percent recurring and 67 percent nonrecurring congestion. When Epps, Cheng, and May (1994) applied Lindley's model to a sample of freeway sections in California, they found that the ratio is highly variable between different segments at different congestion levels. Understanding congestion definition, types, and splits is important in selecting measures to alleviate it. For example, measures to alleviate recurring congestion are not necessarily the same as for non-recurring congestion. A summary of these measures is presented next.

1.1.2 Measures to Alleviate Congestion

Techniques for reducing traffic congestion can be divided into three categories (Rathi and Lieberman, 1989 and Lindley, 1986):

a. Increase of roadway system capacity through construction of additional facilities or other physical improvements to provide additional capacity.

b. Maximization of the use of available capacity through traffic management practices aimed at more efficient use of existing capacity.

c. Reduction of traffic demand through behavioral changes, travel demand management or traffic restraints.

Traffic management has received considerable attention since constructing more freeway facilities (for example, lane addition) to relieve recurring congestion is often politically and socially unacceptable and economically infeasible. Traffic surveillance, ramp metering, network optimization and integration, and incident management are major components of a traffic management system.

Travel demand management techniques may include congestion pricing, parking restrictions, high occupancy vehicles (HOV) lane dedication, and ride sharing. In this study, we are developing a congestion measure to evaluate a system designed to improve the efficiency of an existing freeway system.

Advancement in computer, communication, and information technologies in the past decade enhanced the ability to improve performance of transportation systems in many parts of the world. In the United States, Intelligent Transportation Systems (ITS) was initiated in 1992 to enhance performance of the transportation system through the use of new technologies (U.S. Department of Transportation, 1992).

The implementation of Advanced Traffic Management System (ATMS) and Advanced Traveler Information System (ATIS) components creates the potential for congestion relief in urban areas. The primary feature of these systems is the provision of real time information and control to respond to changing traffic conditions. There are several pilot ATMS/ATIS programs currently being implemented in the US, Europe, and Japan.

1.1.3 Congestion Measurement

Congestion information can be used in a variety of policy, planning, and operational situations. It may be used by public agencies in assessing facility or system adequacy, identifying problems, developing and assessing improvements, and formulating programs, policies, and priorities. It may also be used by the private sector in making location and investment decisions.

Four important attributes of roadway congestion should be quantified (Lomax, Turner, and Shunk, 1997). These are duration, extent, intensity, and reliability. More specifically, duration is defined as the length of time the travel system experiences congestion. Extent refers to the number of people or vehicles affected by congestion. Intensity is the severity of the congestion that affects travel, and reliability is measured in terms of the variation in the other three elements.

Congestion methodologies assign quantitative values to congestion. These methodologies provide a tool that assists the transportation professional, general public, policy makers, business community to communicate with each other, introduce transportation system improvements, and adopt new policies and programs.

Currently, existing congestion measures can be classified according to (a) congestion type (total, recurring, or nonrecurring), (b) roadway type (freeway or arterial), and (c) methodology used for their development (field, surrogate, or simulation). A description of current congestion measures is provided in Chapter 2.

1.2 Description of the Problem

Several methods have been developed to measure congestion. However, many of these methods are not sensitive to variations in traffic speed over time resulting from a traffic management system. They also lack the ability to produce comparable results for various systems with similar congestion levels. Therefore, there is a need for the development of a new measure for quantifying recurring congestion, which is capable of overcoming these limitations if the measure is to be appropriate for measuring the change in congestion resulting from the implementation of ITS components.

1.3 Research Objective

This research addresses the development and testing of a measure to quantify freeway recurring congestion. The scope of the research includes:

a. Identification of speed thresholds for identifying congestion.

b. Development of a methodology for identifying recurring congestion.

c. Development and validation of models to estimate the start time and duration of recurring congestion.

d. Development and application of a measure for quantifying recurring congestion.

e. Investigation of the sensitivity of the measure for seasonal and weekday variations, and data collection frequency.

f. Comparison of the recurring and non-recurring congestion values in addition to the study and CALTRANS estimates of recurring congestion.

1.4 Research Approach

This research was based on analysis of 24-hour, 1-minute loop detector traffic data. The Statistical Package for Social Sciences (SPSS) Version 7.5 (SPSS, 1997) and Fortran PowerStation Version 4.0 algorithms (Microsoft, 1995) were used to analyze and model recurring congestion.

The research was based on 8-month (December 1996 to July 1997) data obtained from loop detectors embedded in two freeway segments (I-94 and M-10) in the Detroit, Michigan metropolitan area. Speed and congestion duration thresholds were developed to detect recurring congestion. Further, a methodology was developed to identify start time and duration of recurring congestion at each detector location. The methodology identifies recurring congestion and smoothes variations below the defined recurring congestion duration threshold. Statistical modeling was used to group the locations that have the same start time and duration. A recurring congestion measure was developed and values were assigned to each location and segment, and the whole system.

Seasonal and weekday variations of the developed measure were tested in addition to the measure's stability over data collection frequency. Moreover, the start time and duration of recurring congestion models were validated using data obtained during August 1997. The recurring and non-recurring congestion estimates were compared in addition to the study and CALTRANS estimates of recurring congestion.

1.5 Summary

Major urban areas suffer from excessive traffic congestion. Several remedies, including traffic management techniques, have been explored and implemented to alleviate congestion. Advanced Traffic Management System (ATMS) applications are being implemented in many parts of the world to test their effectiveness in reducing congestion. The evaluation of these projects is critical for justifying widespread deployment of such technologies.

The existing methods for assigning quantitative values to congestion are not sensitive to variations in traffic speed over time resulting from a traffic management system. More specifically, traffic management techniques are expected to affect average freeway traffic speed rather than volume. There is a need for the development of a new measure for quantifying recurring congestion, which is capable of quantifying the change in congestion resulting from traffic improvements.

Chapter 2

LITERATURE REVIEW

Congestion measures have been described in the literature since the 1950s. The early efforts toward measuring congestion were centered on empirical relationships. Greenshields (1955) proposed an indicator of the "traffic roughness" of roadway sections. The indicator was equal to the product of speed and direction changes over a section of a roadway.

Several other methods have been proposed for assigning a quantitative measure to congestion. Level of Service (LOS) is a widely used measure among traffic agencies. It is defined in the Highway Capacity Manual (HCM) in terms of density for freeways, average travel speed for arterial roads, and average stopped delay for signalized intersections (HCM, 1994). Other queuing-related, travel time, delay, and speed measures have also been used to quantify congestion. Congestion indices have also been developed to quantify traffic congestion on an areawide basis. A summary of congestion measurement approaches follows.

2.1 Current Congestion Measurement Methodologies

As mentioned previously, there are currently several methods for quantifying total, recurring, and nonrecurring congestion. In this chapter, a review of these methodologies is presented with emphasis on total and recurring congestion aspects.

Measuring nonrecurring congestion is beyond the scope of this research. The methodologies are presented in this chapter in a chronological order of evolution and interconnection.

2.1.1 Congestion Severity Index

The Congestion Severity Index (CSI) is a measure of freeway delay per million vehicles-miles of travel (Lindley and McDade, 1988). The methodology uses the Highway Performance Monitoring System (HPMS) database in urban areas with populations of 50,000 or more (Lindley, 1986). Congested conditions occur when the volume to capacity ratio (v/c) exceeds the 0.77 threshold value (which represents the boundary between LOS C and D), and travel speed is less than 55mph (HCM, 1985). The methodology's v/c threshold corresponds to the boundaries between LOS D and E in the 1994 HCM. The methodology uses the 1965 HCM to estimate freeway capacity based on number of lanes and adjustment factors for lane width, lateral clearance, truck presence, and terrain (Lindley, 1986).

Based on traffic data collected on the Washington, D.C. freeways, the methodology developed twelve 24-hour volume profiles that represent typical urban freeway traffic patterns for various peak hour percentage and directional factors (Lindley, 1986). By using these volume profiles, the HPMS data (peak hour data) were expanded to give hourly traffic volume estimates of each freeway section.

This methodology assumes that recurring congestion occurs 260 days per year in order to calculate the total annual congested vehicle miles of travel. Nonrecurring congestion conditions were estimated by using total incident rates. The rates associated with freeways with adequate shoulders and freeways with no shoulder are 200 and 79 incidents per million vehicle miles of travel, respectively (Lindley, 1986). Delays are calculated based on average travel speed varying between 30 and 54 miles per hour for *v/c* ratios between of 1.0 and 0.77. An average speed of 20 mph is assumed for *v/c* ratios greater than 1.0 (Lindley, 1986).

The CSI, in vehicle hours of delay per million miles of travel, can be summarized as shown in the following equation:

$$CSI = \frac{Total\ Freeway\ Delay\ (Vehicle - Hours)}{Freeway\ Vehicle - Miles\ of\ Travel\ (Millions)} \qquad (1)$$

Turner (1992) concluded that a CSI value greater than 24,000 vehicle hours of total delay per million miles of travel represents undesirable area congestion.

The CSI methodology is capable of measuring total, recurring, and nonrecurring congestion from a readily available data (HPMS database). It is also simple to use and neither time consuming nor labor extensive. It can be used to study both statewide networks and individual road sections.

However, there are some questions regarding the accuracy of the results (Epps, Cheng, and May, 1994). First, nationwide, only about 50 percent of road sections are included in the HPMS database. Expansion factors and assumed hourly distributions are used to convert the results obtained from the database into statewide estimates. A third source of error involves the estimation of hourly directional traffic volumes from the twelve 24-hour volume profiles based on the traffic characteristics of two Washington, D.C. freeways. Fourth, the measure is based upon the assumption that the maximum free flow speed is 55 mph, while higher free flow speeds occur in real freeway traffic conditions. The fifth source of error rises from the measure's assumption that a linear relationship between *v/c* (from 0.77 to 1.00) and speed (from 30 to 55 mph) exists during LOS E (operations at capacity) traffic conditions. Finally, the methodology does not allow comparison with more severe congestion condition (LOS F) when it truncates analysis at *v/c* ratio equal to one (Boarnet, Kim, and Parkany, 1998). The methodology also does not account for small variations in speed so it cannot be used in evaluating ATMS.

2.1.2 Roadway Congestion Index

The Roadway Congestion Index (RCI) is based on the daily vehicle-miles of travel (VMT) per lane-mile for freeways and principal arterial street systems combined (Schrank and Lomax, 1997). This index quantifies congestion by comparing the existing value to values identified under congested conditions. The RCI is an empirically derived formula that uses HPMS data. The RCI, which is dimensionless, can be represented as shown in the following equation:

$$RCI = \frac{(VMT/lane\text{-}mi * VMT)_{Fwy} + (VMT/lane\text{-}mi * VMT)_{Art}}{(13{,}000 * VMT)_{Fwy} + (5{,}000 * VMT)_{Art}} \qquad (2)$$

where: VMT = Daily vehicle-miles of travel,

VMT/Lane-mi = Daily vehicle-miles of travel per lane-mile,

Fwy = Freeway, and

Art = Arterial street.

The basic assumption in calculating the RCI is that congestion begins to occur at LOS D as defined in the 1985 HCM (Turner, 1992). Based on historical traffic data from Houston, Texas and an assumed hourly distribution, it was also determined that congestion conditions are equivalent to approximately 15,000 and 5,750 vehicles per lane per day (average annual daily traffic per lane) on individual freeway and principal arterial street sections, respectively (Turner, 1992). The values of 13,000 and 5,000 vehicles per day per lane thresholds for freeways and arterial streets, respectively, were used as an areawide basis for congestion threshold (Turner, 1992).

A RCI value greater than 1.0 represents undesirable level of roadway congestion. Although this index gives an areawide indication of congestion, it is not a measure applicable to segment or site specific evaluation of traffic conditions or variations in travel patterns. An urban area with a RCI of less than 1.0 may still have specific locations that experience congestion, despite the fact that the average level of mobility within the urban area is characterized by uncongested conditions.

The methodology is useful if comparative studies between urban areas are needed. However, this methodology does not distinguish between recurring and nonrecurring congestion. It is only applicable to areawide congestion estimation. It also cannot be used to evaluate ATMS because neither variable (VMT or VMT per lane-mile) changes with the implementation of ATMS components. This methodology also uses the HPMS database and an assumed hourly distribution, which raises the same concerns that have been discussed in previous section.

2.1.3 Lane-Mile Duration Index

The freeway Lane-Mile Duration Index (LMDI) is a measure of the extent and duration of recurring freeway congestion. The LMDI value for each urban area is the sum of the product of congested freeway lane-miles and congestion duration (hours) for individual roadway segments. A congestion travel condition exists if average annual daily traffic volume (AADT) to hourly capacity ratio (AADT/C) is greater than 9.0 (Cottrell, 1991). The LMDI equation is:

$$LMDI = \sum_{i=1}^{n} \left[(Congested\ Lane - Miles)_i * (Congestion\ Duration)_i \right] \qquad (3)$$

where: i = Individual freeway segment,

n = Total number of freeway segments, and

Congestion duration = Duration obtained from an assumed hourly traffic distribution and AADT/C greater than 9.0 as a congestion threshold (hours).

The methodology utilizes the HPMS database, just as the previous two approaches, but uses a different threshold for congested and uncongested conditions. This new threshold corresponds to LOS F where the volume to capacity ratio is greater than 1.0 and the average travel speed is less than 30 mph (HCM, 1985). This methodology also assumes an hourly traffic distribution similar to the previous two approaches.

This methodology only addresses the estimation of recurring congestion delay because of insufficient data for estimating nonrecurring congestion delay was found in the database used (Cottrell, 1991). It is a useful tool if comparative studies between different urban areas are needed. The LMDI methodology also uses the HPMS database, which raises the same concerns that had been discussed in Section 2.1.1.

2.1.4 Traffic Intensity Index

The Traffic Intensity Index (TI) was developed using a database from the Traffic Accident Surveillance and Analysis System (TASAS) in California to represent the traffic demand as a fraction of the supply provided by the freeway facility (Epps, May, and Cortelyou, 1993). The TI index is defined as follows:

$$TI = \frac{1\text{ - }way\ ADT}{(1\text{ - }way\ \#\ of\ lanes) * 1{,}000} \tag{4}$$

where: TI = Traffic Intensity Index (dimensionless),

ADT = Average Daily Traffic (vehicles/day),

1-way # of lanes = Number of lanes in a one way direction, and

1,000 = A reduction factor (vehicles per day per lane).

Using this methodology, freeway segments are classified by the level of recurring congestion. Segments with TI values greater than 20 were defined as experiencing congestion. This methodology does not account for nonrecurring congestion.

Epps, Cheng, and May (1994) modified the equation to include the HCM peak (K) and directional (D) factors. The modified measure, named Directional Peak Hour Demand per Lane, equation is as follows:

$$\textit{Directional Peak Hour Demand per Lane} = \frac{(2\text{ - }way\ AADT) * K * D}{\#\ of\ lanes\ in\ 1 - way} \qquad (5)$$

where: AADT = Annual Average Daily Traffic (vehicles),

K = Peaking Factor, and

D = Directional Factor.

The modified measure is an estimate of the traffic demand per hour per lane during a peak period which can be compared with an acceptable lane capacity (vehicles per hour per lane) to give a demand-capacity ratio (D/C). Demand-capacity ratios near 1.0 indicate near-capacity flow conditions, and D/C values greater than 1.0 indicate recurring congestion conditions.

Freeway sections with directional peak hour demand per lane greater than 2,000 vehicles are defined as congested sections. Recurring congestion and incident levels are also stratified into three levels: low, medium, and high. Then, a 3 x 3 matrix is created to classify freeway sections into nine categories.

The methodology is a modification of the CSI and measures both recurring and nonrecurring congestion based on a surrogate database. However, there are some questions regarding the accuracy of the surrogate database similar to ones that had been discussed in Section 2.1.1. The measure also neither accounts for small variations in traffic speed nor can be used in evaluating ATMS since none of the variables would change with the implementation of ATMS components.

2.1.5 Speed and Delay Rate Indices

The Speed and Delay Rate Indices (SRI and DRI) are based on the HCM free-flow conditions (HCM, 1985 and 1994). Both the SRI and DRI quantify congestion based on a continuous scale with numerical values from 0 to 10. The SRI values correspond to the percentage decrease in speed relative to assumed free-flow condition speed (Lomax, Turner, and Shunk, 1997). On the other hand, DRI values correspond to the increase in travel time relative to travel time under free-flow conditions (Levinson and Lomax, 1996). For example, a SRI value of 5 corresponds to a 50% speed drop due to congestion while a DRI value of 5 corresponds to a time loss of 1 minute per mile (30 mph) on freeways with a free flow speed of 60 mph.

The two indices can be used for freeway or arterial roadways. They are capable of measuring total congestion but not able to distinguish between recurring and nonrecurring congestion. Moreover, these two indices are not able to account for small variations in speed or suitable for evaluating ATMS. The use of a surrogate database and an assumed hourly distribution raises the concerns that have been discussed in Section 2.1.1.

2.1.6 Minute-Miles of Congestion

The Minute-Miles of Congestion (MMC) is a measure of the average section congestion during a given time period and is used by the Illinois Department of Transportation for estimation of congestion on Chicago-area expressways (Polus, 1996).

The measure is based on percent occupancy, which measures the percentage of time each detector is occupied by vehicles. A 30% occupancy, which is equivalent to a density of about 90 vehicles per mile and speed of 25 mph (based on freeway capacity of 2,300 vehicles per hour per lane), is selected as a dividing threshold between the congested and uncongested states.

Therefore, the MMC (in minute-miles) is the sum of the congestion duration multiplied by the length of the corresponding congested section. The MMC equation is as follows:

$$MMC = \sum_{i=1}^{n} Di\ Li \qquad (6)$$

where: i = One-way freeway segment,

n = Total number of freeway segments,

Di = Average duration of congestion for a freeway section i (minutes), and

Li = Length of a freeway section i (miles).

The threshold value of congestion, in MMC units, was arbitrarily selected as 10. This means that the start of the peak period occurs when occupancies of 30% or more are measured for 5 minutes or longer on a two mile section (Polus, 1996).

The methodology measures total congestion and does not distinguish between recurring and nonrecurring congestion. The 5-minute threshold eliminates short-term incidents, which results in under estimation of total congestion. The MMC methodology does not give a measure of the percentage of all traffic subjected to congestion in a day. It also does not account for small speed variations.

2.1.7 Freeway Congestion Index

The Freeway Congestion Index (FCI) was developed to quantify the severity of recurring congestion on Utah freeways by using a speed of 40 mph as a congestion threshold (Thurgood, 1995). Its mathematical expression is:

$$FCI = \sum_{i=1}^{n} \left(\frac{CLM * D_i}{LM_i} \right) \qquad (7)$$

where: FCI = Freeway Congestion Index (lane-mile-hours per lane-mile),

i = One-way freeway segment,

n = Total number of freeway segments,

CLM_i = Total congested lane-miles in freeway segment i (miles),

D_i = Duration of congestion (hours), and

LM_i = Total lane miles in freeway segment i (lane-miles).

To determine the start time of congestion, duration, and extent (lane-miles), the study used instrumented vehicles during defined morning and afternoon peak periods. The study also suggests using aerial photography and employing 1994 HCM density criterion for defining congestion and its extent.

The methodology measures recurring congestion but does not account for nonrecurring congestion. The data collection method (instrumented vehicles) is expensive. Moreover, the methodology only defines recurring congestion when traffic speed falls below 40 mph without specifying a minimum congestion duration threshold.

2.1.8 California Department of Transportation Methodology

The California Department of Transportation (CALTRANS) identified congested freeway segments where speeds less than 35 mph are experienced for at least 15 minutes (Epps, Cheng, and May, 1994). Two methods were used for data collection; namely, loop detectors and vehicles equipped with tachometers. Incident-free weekdays were selected, based on speed plots generated from data collected by loop detectors. In the case of the tachometer-equipped vehicles, data were collected twice a year (in the spring and fall) during incident-free peak periods. From these outputs, maps were created indicating the duration of congestion, average speed, and average travel time. Congestion delay (person-hours of delay) was calculated as the product of the number of vehicles delayed, additional travel time per vehicle due to traveling below 35 mph, and average occupancy (persons per vehicle). The delay equation is as follows:

$$Delay = \sum_{i=1}^{n} Vi * Pi * Li * \left(\frac{1}{Sci} - \frac{1}{35} \right) \qquad (8)$$

where: i = Freeway segment i ,

n = Number of freeway segments,

Vi = Average congested traffic volume along segment i during a typical incident-free weekday (vehicles),

Pi = Average vehicle occupancy along segment i (persons per vehicle),

Li = Length of freeway segment i (miles),

35 = Speed congestion threshold (mph), and

Sci = Average speed during congestion along segment i (mph).

This method measures total and recurring congestion. The speed (35 mph) and minimum recurring congestion interval (15 minutes) are reasonable, but the method neither accounts for small variations in traffic speed nor gives information regarding the probability of congestion occurrence.

2.2 Discussion on the Current Congestion Measures

From the perspective of the data source used in the development of the current congestion methodologies, two major data sources are used: historical and real. The methodologies that are based on already available historical databases use an assumed hourly traffic distribution in order to quantify congestion, while the other techniques use real time speed and hourly traffic distribution data. The first four measures presented above (CSI, RCI, LMDI, and TI) use historical databases. CSI, RCI, and LMDI use the Highway Performance Monitoring System (HPMS) database, while the TI measure uses the Traffic Accident Surveillance and Analysis System (TASAS) in California. The last three measures (MMC, FCI, and CALTRANS) use real time data, from loop detectors or instrumented vehicles.

The first four measures are all derived from the 1985 HCM definition of LOS. The CSI and RCI use LOS D (55 mph) as a threshold value between congested and uncongested conditions, while LMDI uses a LOS F (30 mph). The TI methodology uses a directional peak hour capacity per lane threshold of 2,000 vehicles, which corresponds to LOS D. On the other hand, the MMC uses 30 percent detector occupancy as a congestion threshold, which is generally equivalent to a HCM density threshold of 90 vehicles per lane per mile (severe congestion conditions). The last two measures (FCI and CALTRANS) use slightly higher speed thresholds than the LOS F, namely they use thresholds of 40 and 35 miles per hours, respectively.

With respect to specifying a minimum time interval threshold to define recurring congestion, only the MMC and CALTRANS methodologies do so (5 and 15 minute thresholds, respectively). Finally, none of the current measures is sensitive to short term speed fluctuation within an hour, account for small traffic speed variations or spikes, or estimate the probability of recurring congestion, or can be used to evaluate ATMS. In general, the current recurring congestion measures use data from typical days in order to quantify congestion.

It is also worth mentioning that the DRI and SRI measures are just a variation of the RCI methodology. They are developed to provide measures that are perceived by the public better than the RCI measure. The current recurring congestion measures assumptions and characteristics are summarized in Table 2.1.

2.3 Summary

Several indicators are used to identify recurring congestion based on either travel time, delay, or speed. There are currently many available measures to assign quantitative values to congestion. These measures fall into two major groups based on the databases used; surrogate or real time data. The surrogate models are not sensitive to short term traffic flow fluctuations within the hour. Moreover, some of the current real time data measures account for the short term fluctuations within the hour, but none of them account for the traffic speed spikes or probability of recurring congestion.

Table 2.1 Current Congestion Methodologies Characteristics.

Characteristic	Current Congestion Measure						
	CSI	RCI	LMDI	TI	MMC	FCI	CALTRANS
Data Source	Hist$^{\bullet}$	Hist	Hist	Hist	Real	Real	Real
Threshold Source	HCM	HCM	HCM	HCM	Exp$^{\bullet}$	Exp	Exp
Threshold Measure	V$^{\bullet}$/C$^{\bullet}$	V/C	AADT$^{\bullet}$/C	C	O$^{\bullet}$ D$^{\bullet}$	S$^{\bullet}$	S D
Threshold Value	0.77	0.77	9.0	2,000	30 5	40	35 15
Equivalent S	55	55	30	55	25	40	35
Equivalent LOS	D/E	D/E	F	D/E	F	F	F
Sensitivity to ΔS	No	No	No	No	No	No	No
Probability Factor	No	No	No	No	No	No	No
Evaluate ATMS	No	No	No	No	No	No	No

Note: Hist = Historical.

Exp = Professional experience.

V = Traffic flow (vehicles per hour per lane).

C = Freeway capacity (vehicles per hour per lane).

AADT = Average Annual Daily Traffic (vehicles per day).

O = Detector occupancy (%).

S = Speed (mph).

D = Minimum continuous duration (minutes).

Chapter 3

METHODOLOGY

This study is designed to develop a methodology to identify and quantify recurring freeway congestion. The methodology is based on statistical modeling using real time data from freeways in the Detroit, Michigan metropolitan area. The steps used in this process are: 1) The peak traffic periods are identified from 24-hour 1-minute interval data, 2) Three speeds (30, 35, and 40 mph) and a minimum time interval (15 minutes) are selected as thresholds for defining recurring congestion, 3) The start time and duration of congestion are then determined, 4) A measure for quantifying recurring congestion is developed and applied to the freeway segments studied, and 5) sensitivity analysis and validation of these models are also conducted.

3.1 Study Site

Data were obtained from two freeway segments in the Detroit metropolitan area (Figure 3.1), where an extensive loop detector system is in place. The first segment, on the I-94 interstate freeway, extends between Moross and Van Dyke road (6.0 miles East/West). The second segment, on the M-10 freeway, extends between Grand Boulevard and Meyers Road (8 1/3 miles North/South).

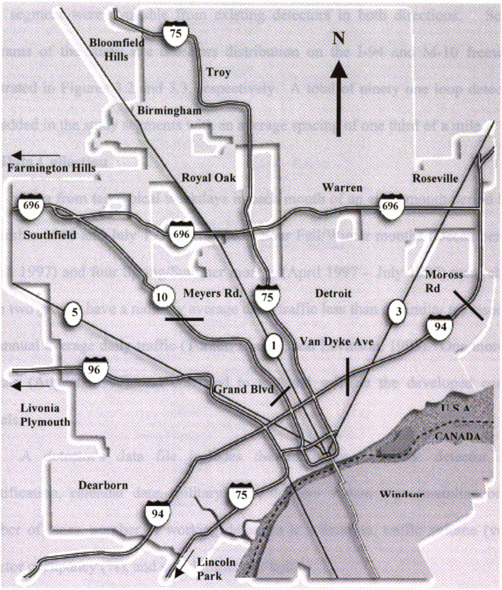


Figure 3.1 Study Site Area Map.

The Annual Average Daily Traffic (AADT) for the first and second study segments is 129,000 and 137,000 vehicle per day, respectively (MDOT, 1996). These two segments were selected because continuous 24-hour 1-minute aggregated data along each segment were available from existing detectors in both directions. Schematic diagrams of the study site detectors distribution on the I-94 and M-10 freeways are illustrated in Figures 3.2 and 3.3, respectively. A total of ninety one loop detectors are embedded in the study segments with an average spacing of one third of a mile.

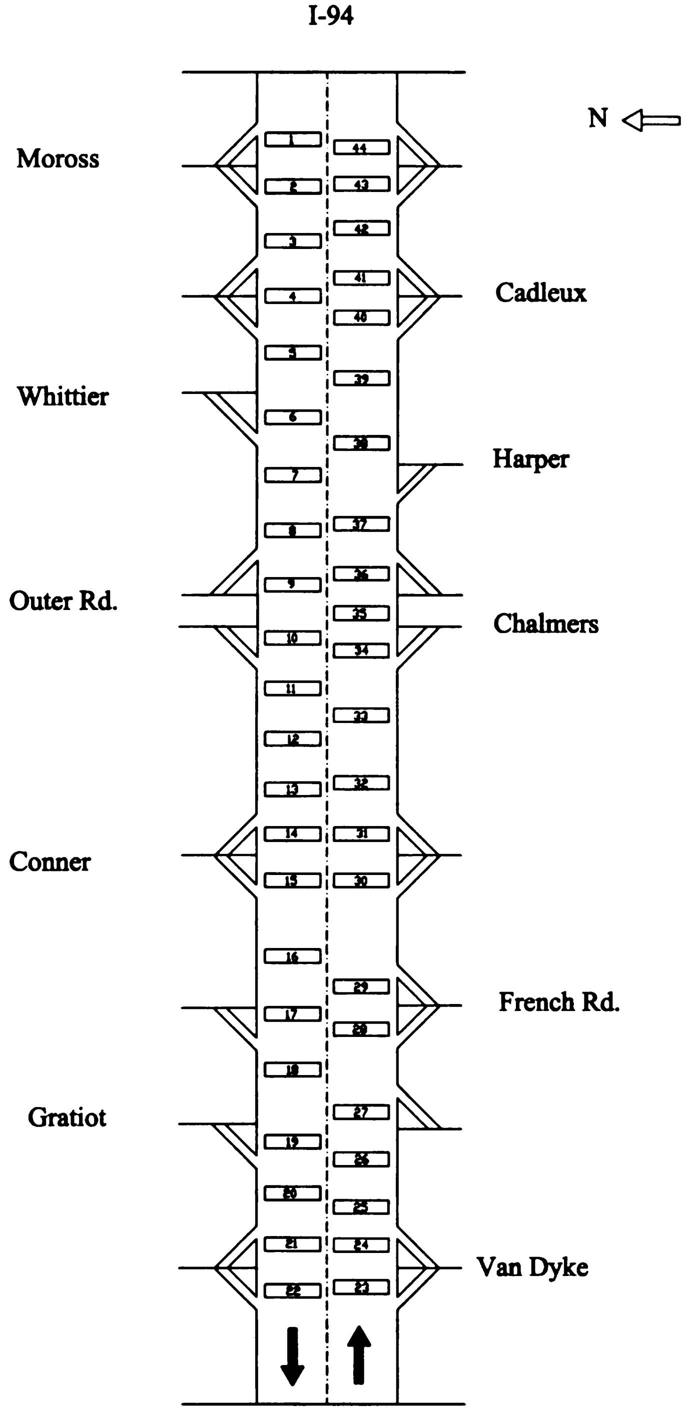
3.2 Data Collection

Data from ten typical weekdays in each month of an eight-month period between December 1996 and July 1997 were used. Four Fall/Winter months (December 1996 – March 1997) and four Spring/Summer months (April 1997 – July 1997) were chosen as these two groups have a monthly average daily traffic less than or similar to, respectively, the annual average daily traffic (Turner, Lomax, and Levinson, 1996). One more month of data (August, 1997) was collected to test and validate the developed congestion models.

A detector's data file includes the following variables: detector location identification, calendar date, military time, detector station type (mainline or ramp), number of lanes, number of working detectors at a location, traffic volume (vehicles), detector occupancy (%), and speed (miles per hour).

3.3 Study Approach

The approach used in this study is based on comparative statistical analysis of data obtained from loop detectors. First, thresholds of speed, the minimum continuous time interval to define recurring congestion, and the severity of congestion are defined



Not to Scale

Figure 3.2 Schematic Diagram of Detector Locations in the I-94 Freeway.

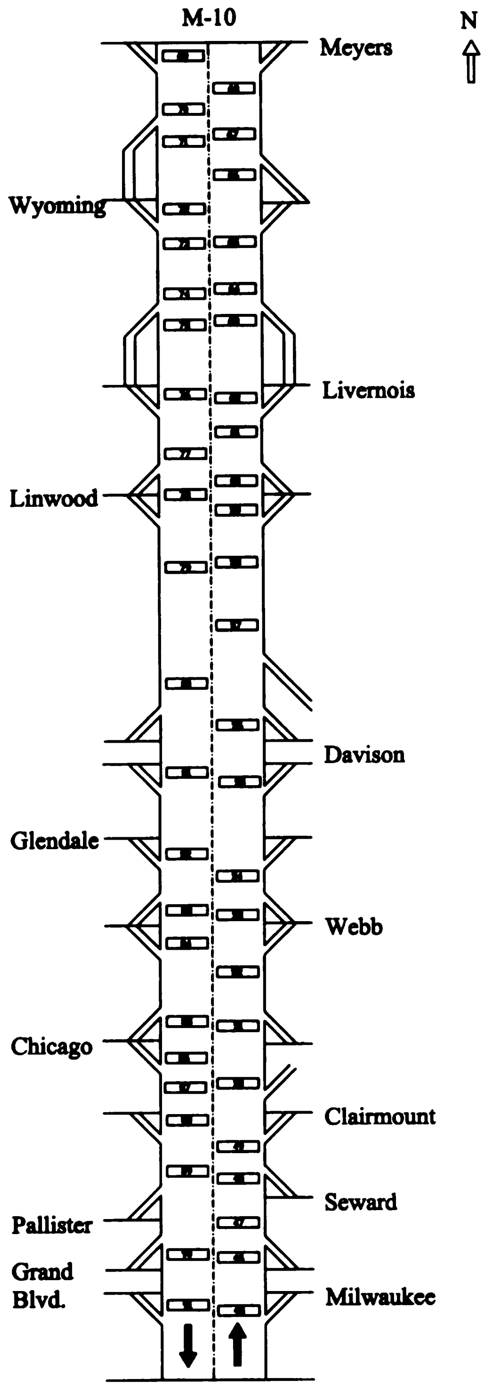


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Figure 3.3 Schematic Diagram of Detector Locations in the M-10 Freeway.

based on the literature review and experience. A methodology to smooth the data from short interval incident-related traffic spikes is also developed. Using this methodology and the defined thresholds, an algorithm is developed to identify start time and duration of congestion at each detector location.

By using this algorithm, a preliminary analysis is conducted to assess the quality and availability of data obtained from detectors and the adequacy of the sample size. This analysis is used to define the AM and PM traffic peak time intervals and limit the study to these intervals. SPSS is used to produce data files that only include the detector locations that have continuous data during the defined peak time intervals.

The start time and duration of recurring congestion are recalculated based on the selected refined database. The Analysis of Variance (ANOVA) statistical tests are used to model recurring congestion at statistically similar locations. The developed models allow for locations that have statistically similar start time and duration of recurring congestion to be grouped together.

Indices are developed to measure and assign quantitative values to congestion. An analysis of seasonal and weekday variations of the developed models are conducted. By using one month of data, these models are tested. A comparison between recurring and nonrecurring congestion estimates is performed. Finally, a comparison between the congestion estimates of the developed and CALTRANS measures is also performed. The development of the freeway congestion measure is presented in detail in the following chapter.

Chapter 4

DEVELOPMENT OF FREEWAY CONGESTION MEASURE

In the previous chapter, a general description of the research methodology was introduced. In this chapter, the methodology is presented in more detail and a freeway recurring congestion measure is developed.

4.1 Definition of Congestion

Several congestion indicators and definitions were introduced in the literature review chapter. Many of these methods define congestion based on the *v/c* ratio used in the HCM to identify LOS thresholds. A few of them define congestion based on a traffic speed threshold. In this study, congestion is defined when the traffic speed falls below a specific threshold value. This definition is illustrated in Figure 4.1 based on a real speed profile from a data collection station on the I-94 study segment. Further, severity of congestion is defined based on the speed increment drop below the specified threshold. In other words, the severity of congestion increases as the speed decreases.

The congestion speed threshold in the 1994 HCM is defined at the LOS E/F breakpoint on freeways (HCM, 1994). This threshold seems to occur at significantly higher speeds (50 instead of 35 mph) and lower densities than in the 1985 edition (HCM, 1985 and 1994). Some states use a congestion speed threshold that is lower than the value specified in the 1994 HCM. For example, a 35 mph speed threshold is used by

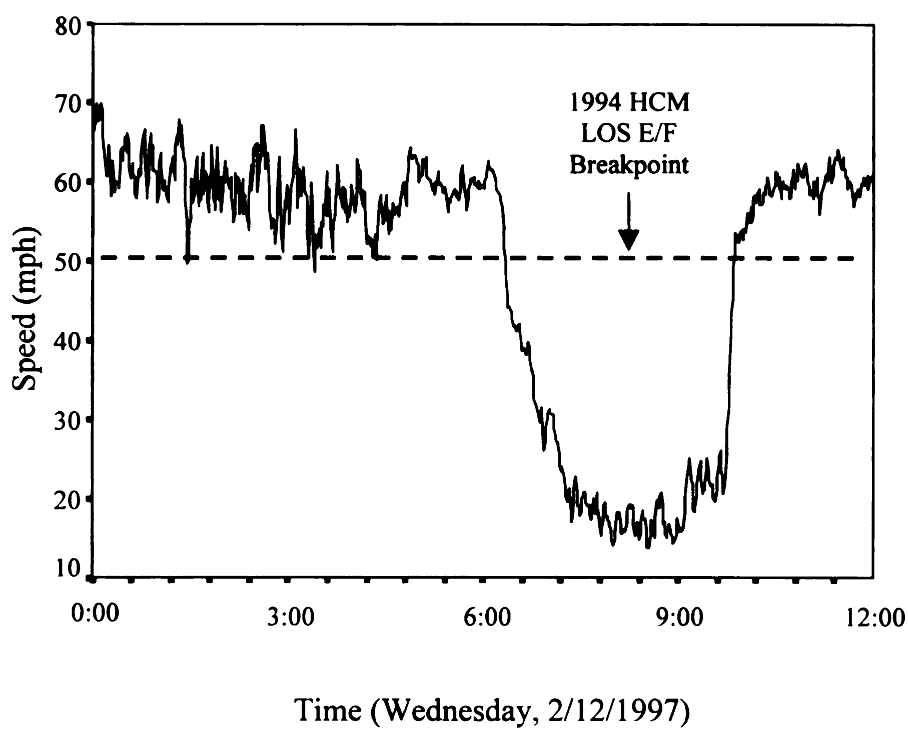


Figure 4.1 Speed Profile on West Bound I-94 at Gratiot Road.

CALTRANS to define congestion (Epps, Cheng, and May, 1994). Some other congestion measurement methods use a speed of 30 mph as a threshold based on the LOS F boundary as defined in the 1994 HCM. It is also believed that a traffic stream speed below 40 mph is a strong indicator that flow is falling into the LOS F (forced-flow) realm. The precise value of the threshold may not be critical, as one study has concluded, in most cases, once speed fell below 50 mph, it also fell below 40 mph (Thurgood, 1996). The speed profiles performed as part of this research also support this conclusion as illustrated in the sample speed profile of Figure 4.1. Based on this discussion, the study proposed testing three speed thresholds: 30, 35, and 40 mph.

4.2 Definition of Recurring Congestion

One of the issues to be resolved in developing a recurring congestion measure is the definition of recurring congestion. The literature review presented in Chapter 2 identified one methodology (CALTRANS) that uses 15 minutes of continuous low-speed operation as a time threshold for defining recurring congestion. In other words, recurring congestion is assumed to occur when the average traffic speed falls below the congestion speed threshold (35 mph in the CALTRANS methodology) for a continuous 15-minute time interval (Epps, Cheng, and May, 1994).

This threshold was adopted for defining recurring congestion. Data from this study show that there is a significant variation in average speed calculated on a minute by minute basis (Figure 4.1). A methodology is needed to smooth the data from short time spikes. This methodology is described in the following section.

4.3 Methodology for Smoothing Recurring Congestion Duration

When the recurring traffic congestion state occurs, short term interruptions are possible where an increase in speed above the congestion speed threshold is observed. A similar situation is encountered during the uncongested traffic state, where this state is interrupted by short term decreases in speed below the congestion speed threshold. Based on this understanding, a methodology has been developed to account for these spikes in the traffic speed and smooth the data.

The methodology will be explained using two scenarios, often encountered during data collection, as examples. The first scenario is characterized by the fact that a congested condition occurs first, followed by an uncongested one, and then congested and uncongested conditions are alternating. The second scenario refers to a situation where uncongested conditions occur first, followed by congested conditions, and then uncongested and congested conditions are alternating. Both scenarios and terminology are illustrated in Figure 4.2.

The methodology's rules are summarized as follows:

$$If\ C_1 \geq 15\ and\ NC_1 < 15, then\ C_f = NC_1 + C_1\ and\ CN_f = 0$$

$$If\ C_1 \geq 15\ and\ NC_1 \geq 15, then\ C_f = C_1\ and\ CN_f = NC_1$$

$$If\ C_1 < 15, then\ C_f = 0\ and\ CN_f = NC_1 + C_1$$

where: C_1 = Congested interval (minutes),

CN_1 = Uncongested interval (minutes),

C_f = Final combined congested interval (minutes), and

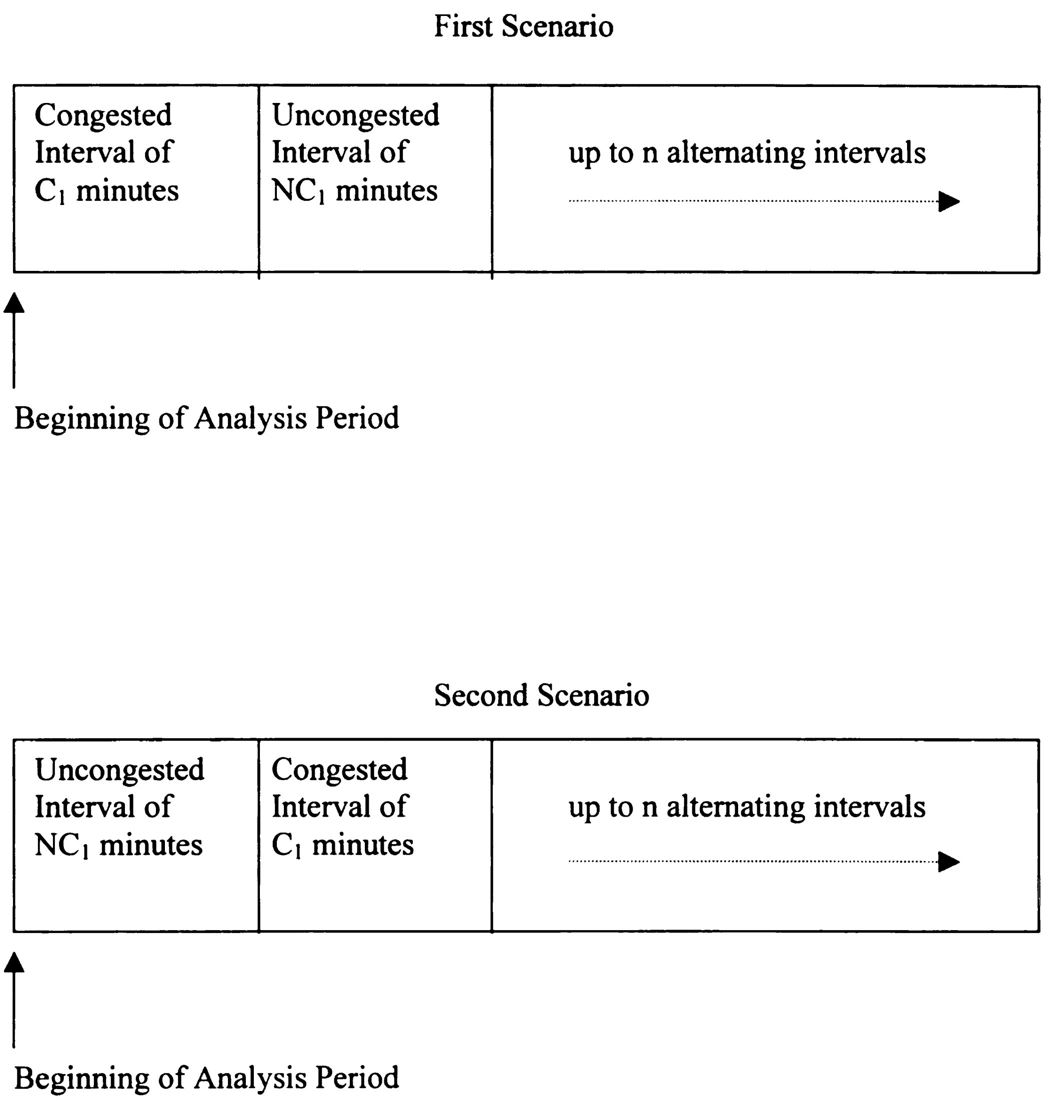


Figure 4.2 Congested and Uncongested Traffic Conditions Scenarios.

CN_f = Final combined uncongested interval (minutes).

Then, the resulting combined traffic conditions are tested against the third consecutive traffic condition by using the same defined rules. Two illustrative examples are presented in Figure 4.3 to explain how the developed methodology works.

The methodology is automated through a FORTRAN program. At each location, the program identifies the following (a customized sample of the program's output is shown in Table 4.1):

1. Duration of congested and uncongested intervals (minutes),
2. Total traffic volume that does not experience recurring congestion (vehicles),
3. Total traffic volume that experiences recurring congestion (vehicles), and
4. Recurring congestion severity value that is defined as the summation of the product of traffic volume and speed difference between the actual and the recurring congestion threshold speed at each minute (vehicle miles per hour).

The methodology was tested on pilot data collected during September, 1996. The start time and duration of congestion for a segment of west bound I-94 during the morning peak period on 9/9/1996 are shown in Figure 4.4. The diagram shows how the methodology smoothes the recurring congestion data and accounts for the small spikes in traffic speed.

4.4 Preliminary Analysis

As part of the preliminary analysis, the methodology was used to calculate the start time and duration of recurring congestion at each detector location along the west bound I-94 freeway test section by using a 6-month database (12/96-5/97). The results indicated that less than two percent of the cases have recurring congestion outside the

(a) Example 1:

Real Traffic Conditions

$C_1 = 18$[*]	$NC_1 = 7$	$C_2 = 15$	$NC_2 = 20$

Smoothed Traffic Conditions

$C_f = 40$	$NC_f = 20$

(b) Example 2:

Real Traffic Conditions

$C_1 = 8$	$NC_1 = 17$	$C_2 = 15$	$NC_2 = 30$

Smoothed Traffic Conditions

$NC_f = 25$	$C_f = 15$	$NC_f = 30$

Note: Time Interval, Minutes.

Figure 4.3 Examples on the Smoothing Methodology.

Table 4.1 Customized Sample Output (6/16/97, 6:00-10:00 a.m.).

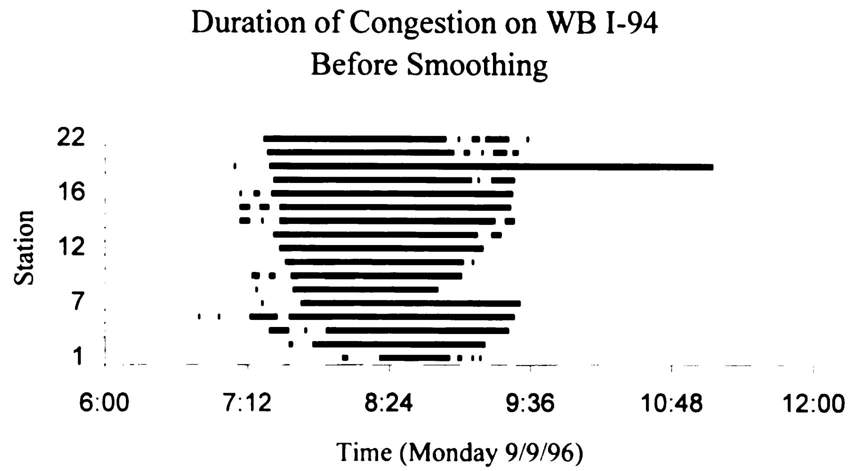
Station I.D.	Congestion (C) or None (NC)	Duration (minutes)	Traffic Volume (vehicles)	Congestion Severity (vehicles-mph)
14	NC	241	17931	0
15	NC	95	8311	0
15	C	50	3888	19035
15	NC	96	5657	0

identified AM and PM peak periods (6:00-10:00 a.m. and 3:00-7:00 p.m., respectively). Therefore, the analysis was limited to these defined peak intervals and data files were reduced only to include records from detectors that were working continuously during this extended AM and PM peak periods.

The preliminary analysis indicated that twelve of the data collection loop detectors were not working during all data collection days. As an example, Figure 4.5 shows the functionality of the loop detectors on the west bound I-94 freeway segment during the six-month period (sixty 24-hour weekdays of data). A value of -1 in the graph is assigned to stations with malfunctioning loop detectors.

4.5 Modeling Start Time and Duration of Recurring Congestion

A ninety five percent confidence interval is used to calculate the mean start time and duration at each detector location. The lower limit of the start time and the upper limit of the duration are used to plot the extended congestion interval at each location.



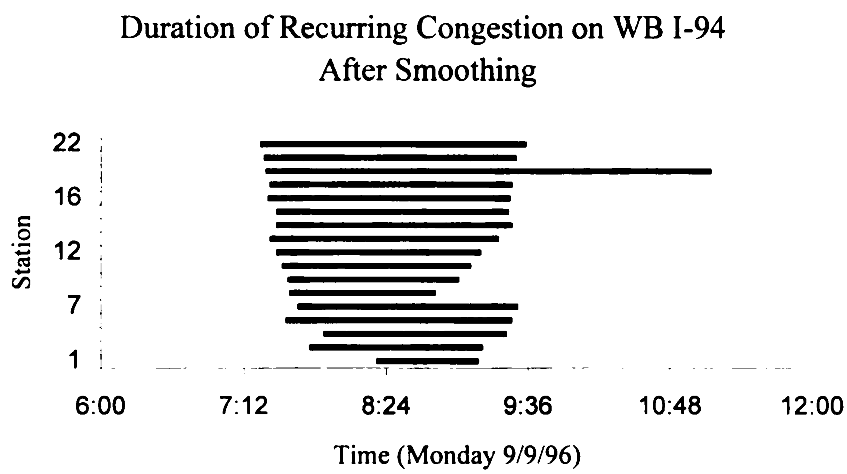
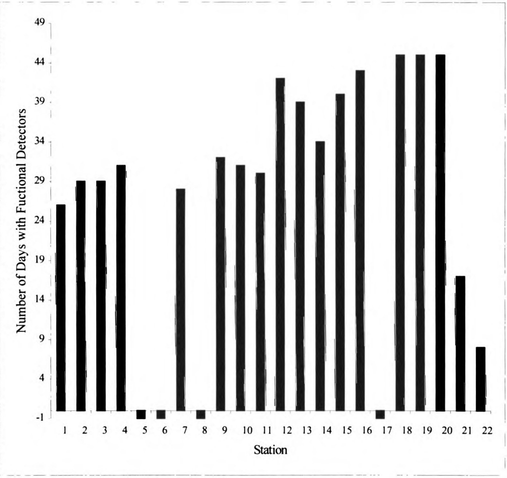


Figure 4.4 Start and Duration of Congestion and Recurring Congestion Before and After Smoothing by using a 35 mph threshold (WB I-94).



Note: -1 denotes that detector was not functioning during data collection period.

Figure 4.5 Functionality of Data Collection Stations on West Bound I-94 Freeway Segment During AM Peak Periods (12/1996-5/1997).

By using these extended congestion interval plots and ANOVA analysis, stations that are statistically similar are grouped together over space. A minimum of five recurring congested days is used as a threshold for defining start time or duration at a location.

4.6 Development of Recurring Congestion Freeway Measures

4.6.1 Probabilistic Recurring Congestion Indices

Based on the discussion throughout this chapter, congestion indices and measures are developed. First, the Probabilistic Location Recurring Congestion Index (PLRCI) is defined as follows:

$$PLRCI_s = P_i \frac{\sum_{j=1}^{Ni} M_{ij}}{Ni} \qquad (1)$$

where: $PLRCI_s$ = Probabilistic Location Recurring Congestion Index at a speed threshold of s mph (dimensionless),

M_{ij} = Recurring congestion index at location i during a time period T in a congested day j (dimensionless),

= V_{Cij}/V_{Tij}

V_{Cij} = Volume of vehicles that have speed less than or equal to the speed threshold at location i during a time period T in a congested day j (vehicles),

V_{Tij} = Total volume of vehicles at location i during a time period T in a congested day j (vehicles),

P_i = Probability of recurring congestion at location i,

= n_i/N_i

n_i = Total number of congested days at location i, and

N_i = Total number of available days at location i.

Equation 1 can also be expressed as follows:

$$PLRCI_s = \frac{n_i}{N_i^2} \sum_{j=1}^{N_i} \frac{V_{cij}}{V_{Tij}} \tag{2}$$

The $PLRCI_S$ is a probabilistic index of the traffic volume that experiences recurring congestion below speed threshold s relative to the corresponding total traffic volume at a specific location and during a defined time interval. In other words, it is an indicator of the probability of a vehicle experiencing recurring congestion at a specific location.

Equation 1 can be expanded to calculate a Probabilistic Freeway Recurring Congestion Index (PFRCI) as follows:

$$PFRCI_s = \frac{\sum_{i=2}^{k-1} PLRCI_i\left(0.5\left(X_{i-1,i} + X_{i,i+1}\right)\right)}{X_{i-1,k} - 0.5\left(X_{i-1,i} + X_{k-1,k}\right)} \tag{3}$$

where: $PFRCI_s$ = Probabilistic Freeway Recurring Congestion Index at a speed threshold of s mph (dimensionless),

$PLRCI_s$ = Probabilistic Location Recurring Congestion Index at location i and speed threshold of s mph (dimensionless),

$X_{i-1,i}$ = Distance between detector i and the immediate upstream detector i – 1 (miles),

$X_{i,i+1}$ = Distance between detector i and the immediate downstream detector i + 1 (miles),

$X_{i-1,k}$ = Total distance between detectors i - 1 and k (miles), and

k = Total number of detectors included in the freeway segment.

By assuming equal spacing of loop detectors, Equation 3 can be simplified as follows:

$$PFRCIs = \frac{1}{k-2}\sum_{i=2}^{k-1} PLRCIi \qquad (4)$$

The $PFRCI_s$ is an index of the probability of recurring congestion along a freeway segment during a specified time interval. It is an indicator of the extent of freeway recurring congestion.

4.6.2 Probabilistic Recurring Congestion Severity Indices

A Probabilistic Location Recurring Congestion Severity Index (PLRCSI) is defined as follows:

$$PLRCSI_s = P_i \frac{\sum_{j=1}^{N_i} s_{ij}}{N_i} \qquad (5)$$

where: $PLRCSI_s$ = Probabilistic Location Recurring Congestion Severity Index at a speed threshold of s mph (mph),

s_{ij} = Speed drop below the threshold s at location i and during a time period T in a congested day j (mph), and

P_i = as defined above.

The $PLRCSI_s$ is an index of the probabilistic speed drop of the traffic below the speed threshold s at a specific location and during a defined time interval. It is an indicator of the severity of recurring congestion at a specified location.

Equation 5 can be expanded to calculate a Probabilistic Freeway Recurring Congestion Severity Index (PFRCSI) as follows:

$$PFRCSI_s = \frac{\sum_{i=2}^{k-1} PLRCSI_i(0.5(X_{i-1,i} + X_{i,i+1}))}{X_{i-1,k} - 0.5(X_{i-1,i} + X_{k-1,k})} \qquad (6)$$

where: $PFRCSI_s$ = Probabilistic Freeway Recurring Congestion Severity Index (mph), and other variables as defined above.

By also assuming equal spacing of loop detectors, Equation 6 can be simplified as follows:

$$PFRCSI_s = \frac{1}{k-2}\sum_{i=2}^{k-1} PLRCSI_i \qquad (7)$$

4.6.3 Freeway System Recurring Congestion Measure

A Freeway System Recurring Congestion Measure (FSRCM) is defined as follows:

$$FSRCM_s = \sum_{i=2}^{k-1} P_i * 0.5(X_{i-1,i} + X_{i,i+1}) * V_{ci} * \left(\frac{1}{s - s_i} - \frac{1}{s}\right) \qquad (8)$$

where: $FSRCM_s$ = Freeway System Recurring Congestion Measure (vehicle-hours),

P_i = Probability of recurring congestion at location i,

$X_{i-1,i}$ = Distance between detector i and the immediate upstream detector i – 1 (miles),

$X_{i,i+1}$ = Distance between detector i and the immediate downstream detector i + 1 (miles),

s = Speed threshold (mph),

V_{ci} = Total volume of vehicles that have speed less than or equal to s (vehicles),

s_i = Average speed drop below the threshold s at location i, and

k = Total number of locations in the freeway segment.

By assuming equal detectors spacing (1/3 of a mile for the study segments), Equation 8 can be simplified as follows:

$$FSRCMs = L_i * \sum_{i=2}^{k-1} Pi * Vci * \left(\frac{1}{s - si} - \frac{1}{s} \right) \tag{9}$$

where: L_i = Average spacing of data collection locations (miles).

The FSRCM is a freeway recurring congestion measure of delay over time and space. It provides a quantitative value to freeway recurring congestion on a segment or areawide basis.

4.7 Summary

Definitions of congestion and recurring congestion were developed based on a speed threshold (30, 35, and 40 mph). A methodology was also developed to detect and smooth recurring congestion duration based on speed and minimum congestion duration thresholds.

The AM and PM peak period intervals of 6:00-10:00 and 3:00-7:00 p.m., respectively, were identified based on a preliminary analysis. Further analyses in the following chapters are limited to these peak intervals.

A methodology for modeling the start time and duration of recurring congestion of a freeway segment was introduced. Location and freeway recurring congestion indices and measures were also developed.

These indices and measures are capable of identifying and quantifying freeway recurring congestion on a location, segment, or areawide basis. They also account for small variations in traffic speed within the peak periods and utilize a recurring congestion probability factor. These measures are also suitable for use in evaluating ATMS because they account for small variations of traffic speed. The following chapter presents the analysis and results of implementing this methodology.

Chapter 5

ANALYSIS AND RESULTS

The testing was based on real time data from loop detectors embedded in an urban freeway network. Analyses were performed on two freeway segments during both the AM and PM peak periods. Testing recurring congestion index (M) equality at three speed thresholds is introduced in the first section and data quality and results follow.

5.1 Freeway Recurring Congestion Speed Thresholds

The hypothesis that the recurring congestion index (M) values are equal for three speed thresholds (30, 35, and 40 mph) is tested. This test is used to determine the sensitivity of this index to the selected speed threshold and accordingly, select threshold or thresholds for M measurement.

Tables 5.1 and 5.2 show the results of testing the hypothesis on two freeway segments. The recurring congestion index is the percentage of vehicles that experience speed below the speed threshold relative to the total volume of vehicles during a peak period. The analysis was performed by using records from congested stations on the WB I-94 AM and NB M-10 PM freeways (a minimum sample size of 5 congested days was used as a selection threshold). ANOVA was performed to compare the three M mean values at each station. The recurring congestion index (M) is not statistically different at significance level of 5% (Tables 5.1 and 5.2) when using each of the three proposed

Table 5.1 Mean Recurring Congestion Indices Comparison (WB I-94 AM Peak).

Station I.D.	Sample Size (N)	Mean M[1] (%)			Standard Deviation of M (%)			P-value[2] (%)
		Threshold (mph)			Threshold (mph)			
		30	35	40	30	35	40	
2	7	26	28	29	20	21	21	95.6
3	5	32	34	41	21	24	24	78.7
4	8	36	37	42	23	23	23	84.7
7	5	26	36	41	14	17	18	39.6
9	8	36	41	49	23	21	23	48.6
10	8	39	48	56	22	20	22	30.2
12	7	42	49	57	22	22	20	42.4
13	5	43	58	60	16	13	13	17.1
14	8	28	35	40	18	17	17	38.4
15	16	26	32	35	16	15	17	22.4
16	23	23	29	32	16	16	16	17.1
18	19	21	28	34	17	16	18	7.8
19	39	29	36	41	15	16	17	0.4
20	25	33	38	44	16	16	17	6.8
21	27	44	47	49	14	13	13	35.0

Note:
1 Mean recurring congestion index.
2 P-value = Probability of (F-statistic > F-observed) assuming that the observed means are statistically equal at the three speed thresholds.

Table 5.2 Mean Recurring Congestion Indices Comparison (NB M-10 PM Peak).

Station I.D.	Sample Size (N)	Mean M[1] (%) Threshold (mph)			Standard Deviation of M (%) Threshold (mph)			P-value[2] (%)
		30	35	40	30	35	40	
45	13	28	33	34	16	18	18	59.8
46	16	29	36	40	17	19	18	23.1
47	14	25	33	37	19	20	20	25.0
48	19	26	31	36	16	17	18	20.2
49	8	45	54	56	13	16	17	33.7
51	13	28	38	49	21	23	25	8.2
52	9	31	45	52	20	21	25	13.3
59	5	13	18	23	7	7	4	8.1

Note: 1 Mean recurring congestion index.
2 P-value = Probability of (F-statistic > F-observed) assuming that the observed means are statistically equal at the three speed thresholds.

speed thresholds at 22 of 23 stations. Station 19 is the exception.

Further analysis of the three M mean values by using the Bonferroni multiple comparison tests indicates the same previous results. Table 5.3 shows the Bonferroni multiple comparison tests for station 19 which indicates that the M mean value obtained by using a 35 mph threshold is not statistically different than that obtained by using 30 or 40 mph threshold at a level of significance of 5%. The table also shows that the M mean values obtained by using a 30 mph threshold is statistically different than that obtained by 40 mph threshold at any reasonable significance level.

The above analyses show that if the traffic speed drops below 40 mph it nearly always falls below 30 mph. The differences in the mean M values at station 19 may be attributed to the location of the station in the upstream area of an exit ramp to a major road (Van Dyke Road).

To study station 19 in more detail, the average speed profiles for station 19 and another station (station 2) where the M mean values, by using either one of the three thresholds, are not statistically different (Figure 5.1). The average slope of the speed profile curve where the speed falls from 40 to 30 mph is approximately the same (-0.7 mph per minute) for stations 2 and 19. On the other hand, the average slope of the speed profile curve where the speed rises from 30 to 40 mph for station 2 (2.0 mph per minutes) is approximately three times that of station 19 (0.7 mph per minute). This indicates that both stations 2 and 19 have the same pattern when the speed falls under 40 mph. The patterns of these stations are different when the speed rises from 30 to 40 mph. This indicates that station 19 has a unique congestion pattern different than other stations.

It can be concluded that the recurring congestion index (M) is not statistically

Table 5.3 Comparison of Recurring Congestion Index (M_i) by Using Three Speed Threshold (Station 19).

Speed Threshold I (mph)	Speed Threshold J (mph)	Mean Diff I-J[1] (mph)	Std. Err.[2] (mph)	P-value[3]
30	35	-0.07	0.04	0.14
	40	-0.12*	0.04	0.00
35	30	0.07	0.04	0.14
	40	-0.05	0.04	0.48
40	30	0.12*	0.04	0.00
	35	0.05	0.04	0.48

Note:
1 Difference between mean Mi by using thresholds I and J.
2 Standard error between mean Mi by using speed thresholds I and J.
3 P-value = Probability of (t-statistic > t-observed) assuming that the observed mean differences are statistically equal at the corresponding speed thresholds.
* The mean difference of Mi is significant at the 0.05 level.

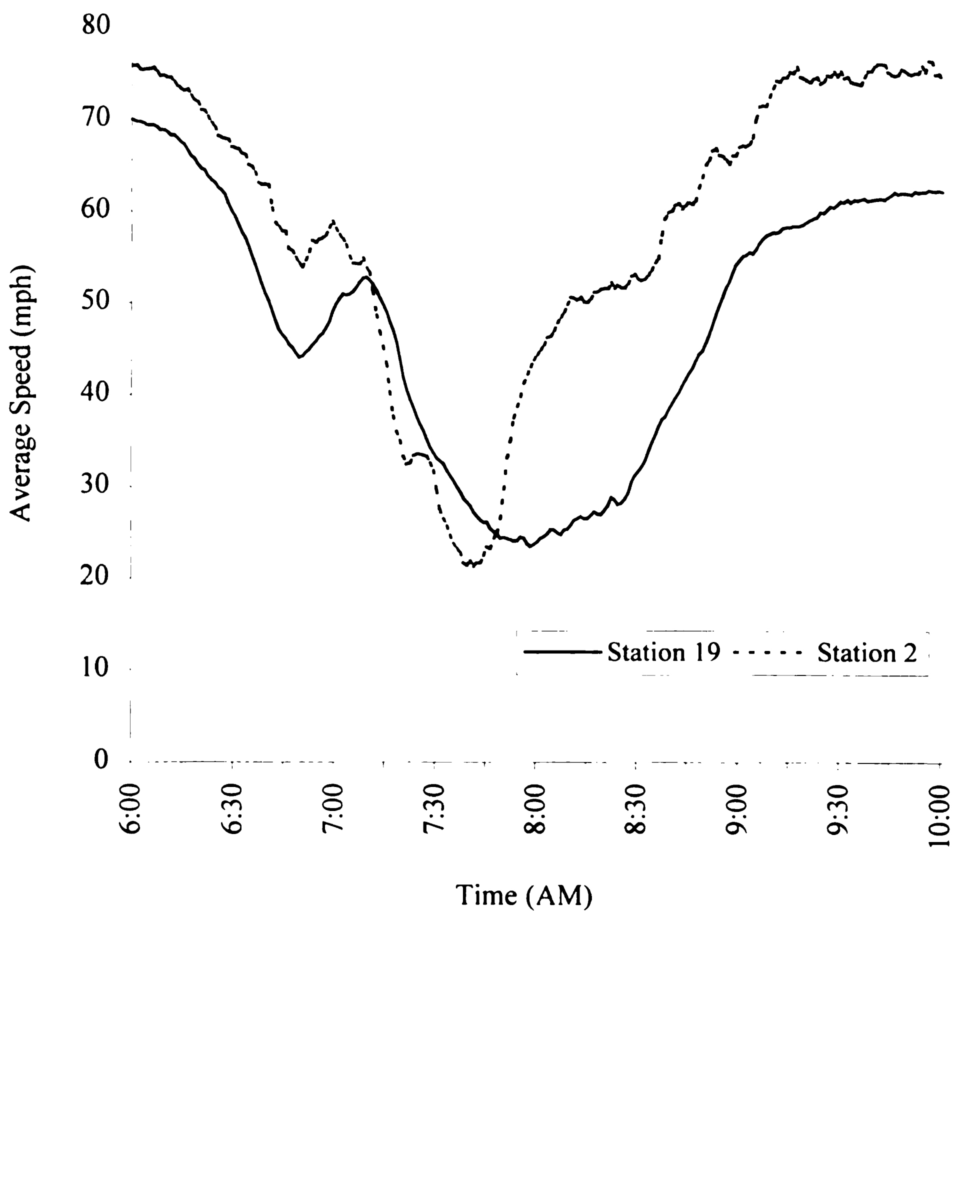


Figure 5.1 Speed Profiles for Stations 2 and 19 (12/1996-7/1997).

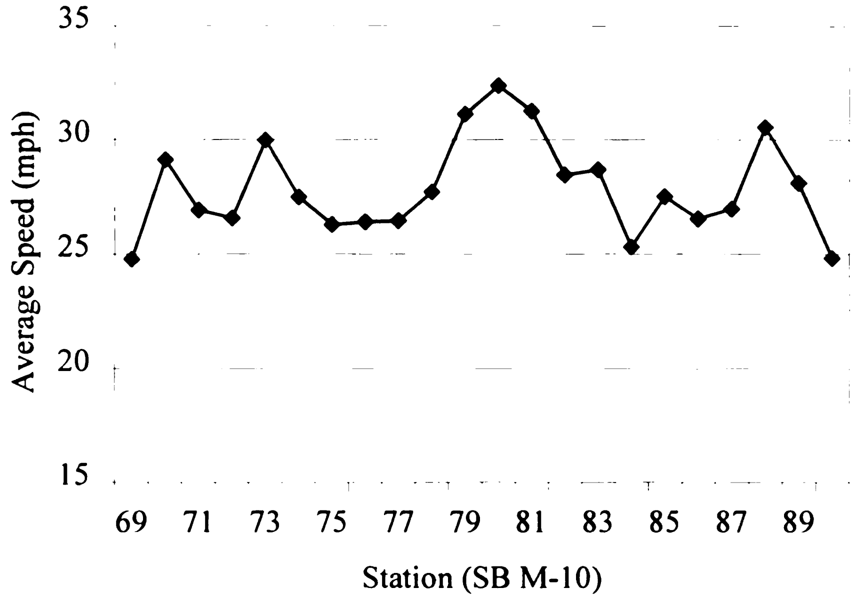
different for each of the three selected speed thresholds of 30, 35, and 40 mph. In other words, to measure recurring congestion it is sufficient to use any one of these speed thresholds. Accordingly, the analyses and results throughout the rest of this study will be presented by using one speed threshold (35 mph).

Figure 5.2 shows the average speed profile during the AM peak periods on the WB I-94 and SB M-10 freeways. This figure shows that the average speed on these two segments during the AM congestion ranges between 25 to 30 mph, except for a few stations. This pattern also confirms the previous conclusion in this regard; the recurring congestion index is the same regardless of speed threshold values of 30 mph and above.

5.2 Data Availability

The functionality of the detectors varies from station to station, freeway to freeway, and the AM to PM peak periods as shown in Tables 5.4 and 5.5. Twelve of the ninety one detectors (13%) were not operational during the test period. The total available data on each of remaining 79 detectors ranged from one day to seventy two days (of the 80 days in the sample). The average number of days of data are 37 and 42 per detector during the AM and PM peak periods, respectively. The average number of days of data are 38, 29, 31, and 56 days per detector on the WB I-94, EB I-94, NB M-10, and SB M-10 freeways, respectively.

In general, congestion occurs on west bound I-94 (inbound to the city center) during the morning peak period. Non-congested traffic conditions prevail on both west and east bound I-94 during the PM peak period. Congestion exists on both south and north bound M-10 during the AM and PM peak periods.



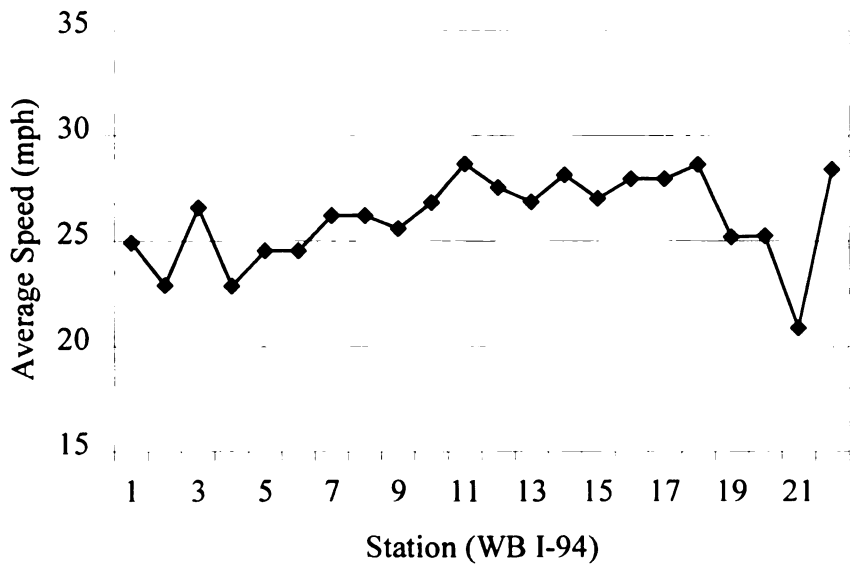


Figure 5.2 Average Speed on WB I-94 and SB M-10 Freeways (AM Peak Periods).

Table 5.4 Data Availability on the I-94 Study Segment.

West Bound					East Bound				
Station I.D.	Functional Days		Rec. Cong. Days		Station I.D.	Functional Days		Rec. Cong. Days	
	AM	PM	AM	PM		AM	PM	AM	PM
1	35	44	3	0	23	-1	-1	-1	-1
2	45	52	7	1	24	55	58	0	17
3	42	51	8	0	25	8	12	0	1
4	37	40	10	1	26	-1	-1	-1	-1
5	-1	-1	-1	-1	27	3	1	0	0
6	-1	-1	-1	-1	28	7	8	0	0
7	32	44	5	1	29	64	67	0	12
8	-1	-1	-1	-1	30	64	67	0	2
9	42	45	10	2	31	-1	-1	-1	-1
10	50	55	14	2	32	-1	-1	-1	-1
11	49	55	7	2	33	54	56	0	0
12	50	62	11	0	34	36	37	0	1
13	49	63	7	0	35	5	6	0	0
14	44	59	17	2	36	9	9	0	0
15	49	62	26	1	37	60	63	0	1
16	53	60	33	2	38	26	30	0	2
17	-1	-1	-1	-1	39	13	12	0	0
18	50	54	30	2	40	61	63	0	2
19	50	53	48	4	41	36	35	0	3
20	50	54	29	2	42	-1	-1	-1	-1
21	26	31	23	8	43	60	63	0	3
22	8	11	4	2	44	54	60	0	8

Note: -1 denotes that detectors did not function during the active data collection period (80 days).

Table 5.5 Data Availability on the M-10 Study Segment.

North Bound					South Bound				
Station I.D.	Functional Days		Rec. Cong. Days		Station I.D.	Functional Days		Rec. Cong. Days	
	AM	PM	AM	PM		AM	PM	AM	PM
45	45	50	0	17	69	17	19	1	1
46	65	63	0	24	70	16	18	2	0
47	13	50	0	21	71	58	69	34	0
48	39	58	0	26	72	62	72	40	0
49	34	42	0	20	73	46	52	10	8
50	-1	-1	-1	-1	74	70	75	26	0
51	59	70	0	16	75	61	70	27	1
52	59	70	0	17	76	67	74	31	2
53	56	60	0	11	77	18	28	10	7
54	67	69	0	4	78	68	71	32	1
55	11	21	1	1	79	67	73	16	3
56	66	70	0	4	80	8	11	3	0
57	-1	-1	-1	-1	81	10	10	2	0
58	-1	-1	-1	-1	82	70	76	4	0
59	48	55	0	10	83	70	75	3	0
60	34	44	1	4	84	72	75	3	0
61	9	12	0	1	85	28	29	2	1
62	57	62	1	2	86	70	72	2	2
63	39	45	1	3	87	72	74	2	1
64	35	46	1	1	88	51	54	1	1
65	4	5	0	0	89	70	74	11	0
66	7	8	0	0	90	65	69	15	0
67	8	8	0	0	91	66	69	16	1
68	26	31	0	1	_	_	_	_	_

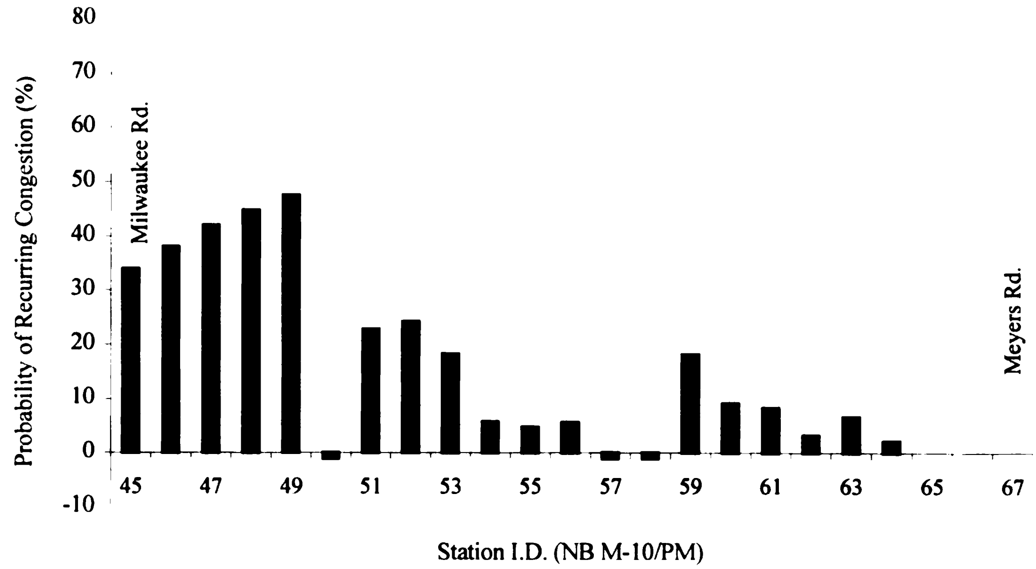
Note: -1 denotes that detectors did not function during the active data collection period (80 days).

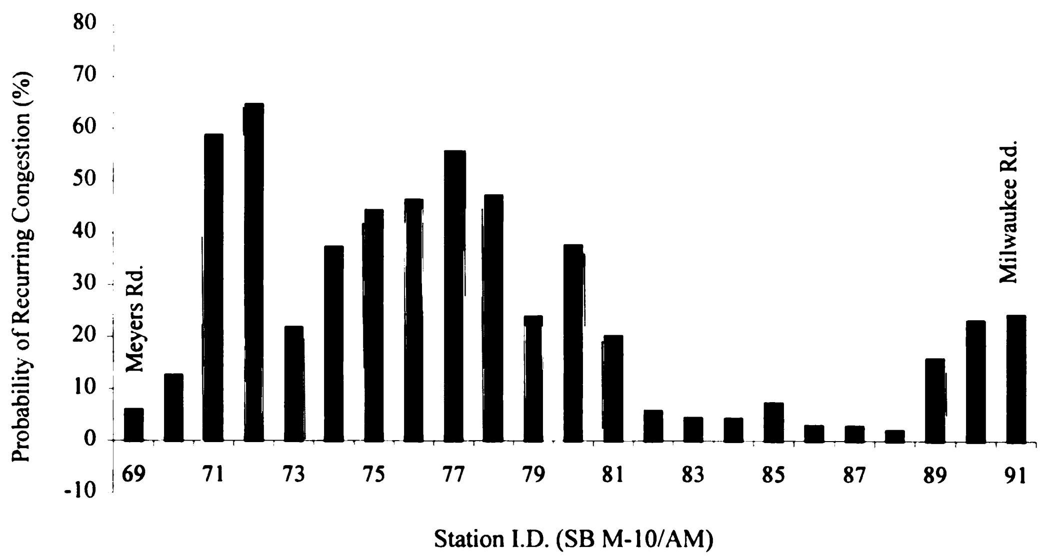
5.3 Freeway Recurring Congestion Probability

The probability of recurring congestion at a data collection station is defined as the ratio of the number of congested days at that station over the number of days with valid data. The probability of congestion on south and north bound M-10 during the AM and PM peak period is shown in Figure 5.3. In general, the probability of congestion during the AM peak period increases as far as station 77, then decreases as traffic flow approaches the city center (south of Milwaukee Rd.). The same pattern applies during the PM peak period as traffic flow departs the city center. This pattern can be explained by the fact that suburban commuters destination is to the city center during the AM peak period and out of the city center during the PM peak period. Deviation of stations 71 and 72 (SB M-10) from this pattern during the AM peak period is recommended for further analysis in future studies by collecting detailed lane-by-lane data.

The above pattern also applies to the I-94 freeway segment as shown in Figure 5.4, except that congestion only occurs in one direction, namely west bound, during the AM peak period. In general, east bound I-94 does not experience congestion either during the AM or PM peak periods. Deviation of stations 19 and 21 (WB I-94) from this pattern during the AM peak period is attributed to the locations of these stations upstream an exit ramp to a major road (Van Dyke Rd.) that results in a different congestion pattern.

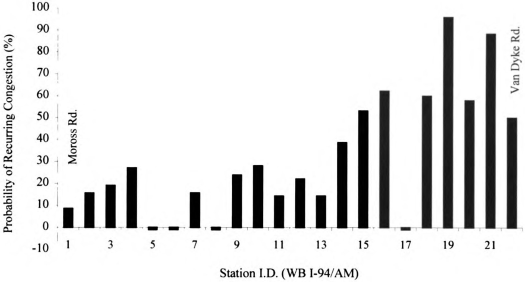
Table 5.6 summarizes the recurring congestion probabilities of the freeway segments. The table shows that the average probability of recurring congestion on both segments during the AM peak interval is higher than that of the PM peak interval. The difference in the average recurring congestion probability between the AM and PM peak

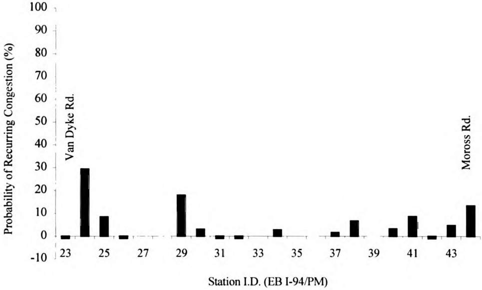




Note: Negative value denotes that a station was not functioning during the data collection period.

Figure 5.3 Recurring Congestion Probability on the M-10 Freeway Segment.





Note: Negative value denotes that a station was not functioning during the data collection period.

Figure 5.4 Recurring Congestion Probability on the I-94 Freeway Segment.

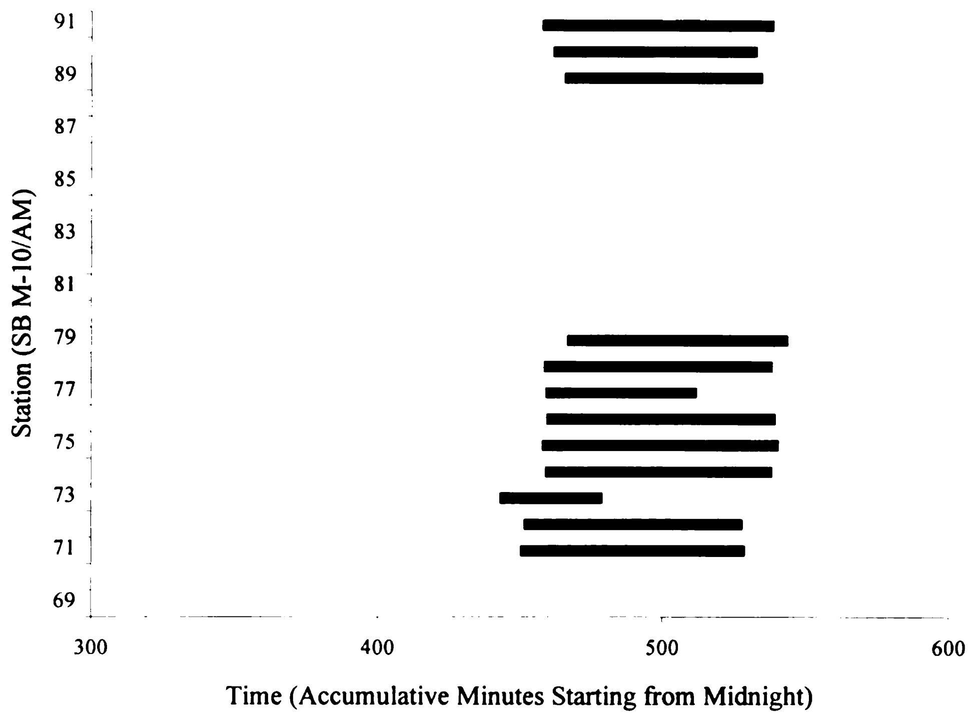
Table 5.6 Summary of Recurring Congestion Probability (%).

Freeway	M-10		I-94	
	SB/AM	NB/PM	WB/AM	EB/PM
Minimum	2	0	9	0
Maximum	65	48	96	29
Average	25	16	39	6

periods on the I-94 freeway is higher than that on M-10. The table also shows that the I-94 freeway is more congested than M-10 during the AM peak period.

5.4 Start Time and Duration of Freeway Recurring Congestion

Figures 5.5 and 5.6 show the start time and duration of recurring congestion on M-10 and I-94 freeways during the peak periods. The average AM peak period recurring congestion on the I-94 freeway starts 34 minutes earlier than on the M-10. The average AM peak period recurring congestion start times on the I-94 and M-10 freeways are 7:04 and 7:38 a.m., respectively. However, the average AM peak period recurring congestion on both freeways ends approximately at the same time with a difference of 5 minutes (8:55 and 8:50 a.m. for the I-94 and M-10 freeways, respectively). This is because the AM peak period recurring congestion on the I-94 freeway lasts longer than that of the M-10, namely 111 and 72 minutes, respectively.



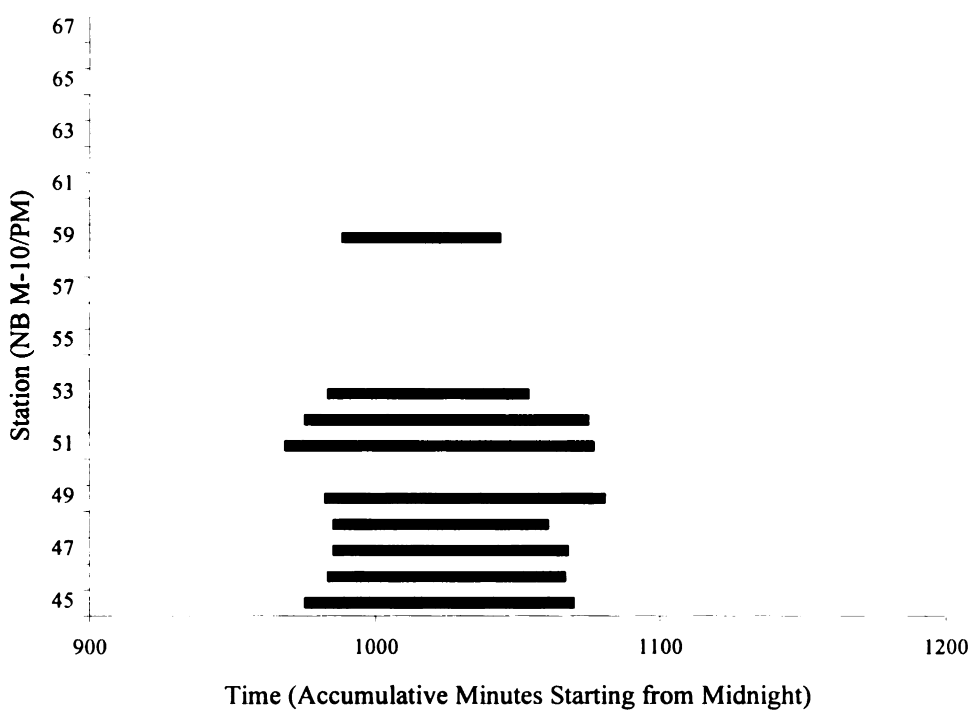


Figure 5.5 Recurring Congestion Start Time and Duration on the M-10 Freeway.

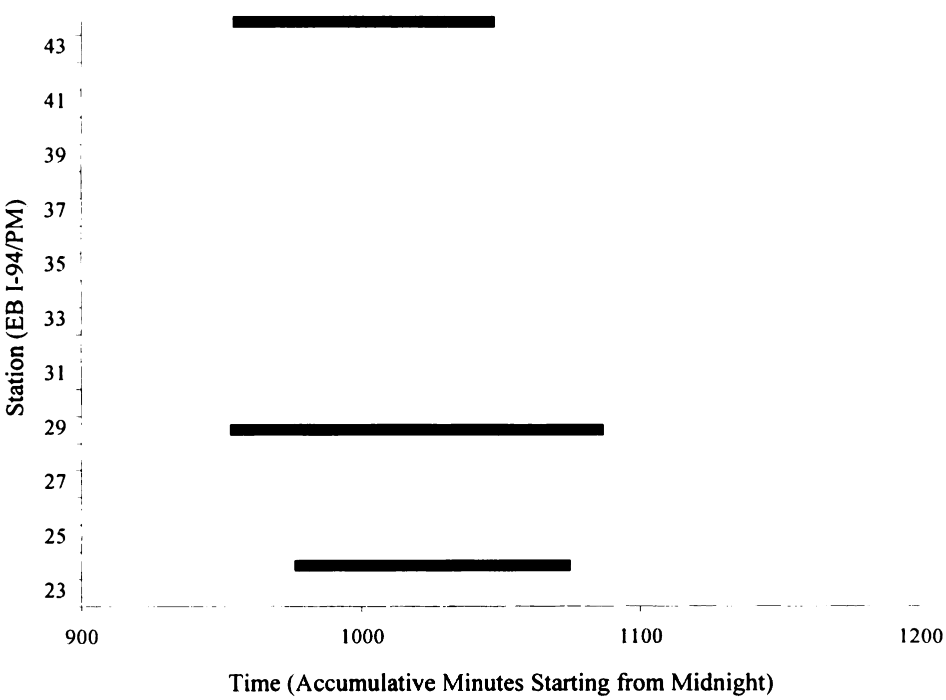


Figure 5.6 Recurring Congestion Start Time and Duration on the I-94 Freeway.

The average start time and duration of the PM peak period recurring congestion on the M-10 freeway are 4:20 p.m. and 86 minutes, respectively. This average PM peak period recurring congestion lasts 14 minutes longer than that of the average AM peak period (86 and 72 minutes, respectively). The PM peak period recurring congestion on the I-94 freeway is not significant.

The average AM peak period recurring congestion extends for a greater distance on the I-94 freeway than on M-10. In other words, the AM peak period recurring congestion covers more distance (miles) on the I-94 freeway than on M-10.

The study of the AM peak period recurring congestion pattern reveals the following: (a) as the traffic flow moves toward the city center, recurring congestion on both freeways starts at a later time, and (b) the upstream half of both freeways has a recurring congestion duration longer than the downstream half. In other words, the AM peak period recurring congestion decreases as the traffic flow moves towards the city center. The same pattern applies to the PM peak period on the M-10 freeway when the traffic flow moves away from the city center; i.e. recurring congestion starts at a later time and lasts for a shorter duration. No specific pattern can be applied to the PM peak period recurring congestion on the I-94 freeway because it is not significant.

The development of a data sampling plan involves: (a) establishing a baseline for future analyses, (b) determining the most appropriate time intervals and threshold speed to define congestion, and (c) testing the stability of this measure of congestion over time and distance. The sampling plan was established by grouping locations based on the statistical similarity of the freeway recurring congestion start time and duration (a minimum sample size of five congested days).

Figures 5.7 and 5.8 show that the freeway locations can be grouped based on the statistical similarity of the recurring congestion start time and duration. A significance level of 5% is used as an analysis threshold (a minimum sample size of five congested days was used). Figures 5.7 and 5.8 support the same recurring patterns that were discussed throughout this section.

In summary, this plan allows reduction of (a) the number of data collection locations, and (b) the frequency of data collection during the peak period necessary for recurring congestion measurement. For example, sampling at one location between stations 7 and 13 (Figure 5.8) during the AM peak period is sufficient to estimate the recurring congestion along that freeway segment (at a 5% significance level).

5.5 Freeway Recurring Congestion Indices and Measures

5.5.1 Probabilistic Location Recurring Congestion Indices

The Probabilistic Location Recurring Congestion and Severity Indices (PLRCI and PLRCSI) were calculated for the study freeway segments and are presented in Tables 5.7 through 5.10. The calculations are based on the mean values of the probability of congestion, recurring congestion index, and severity of recurring congestion index at each station (using Equations 2 and 5 in Chapter 4).

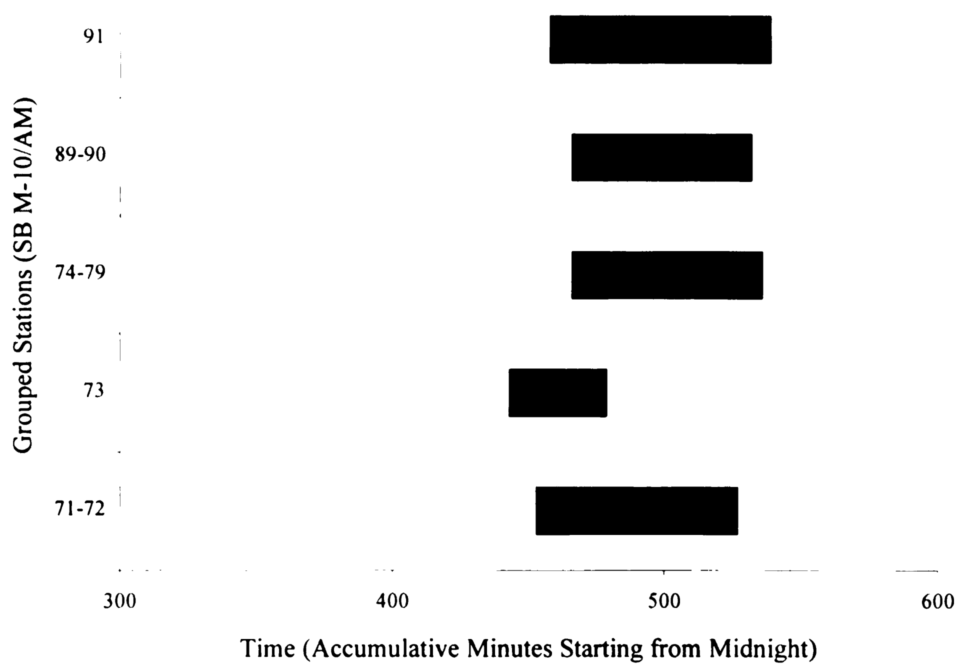
A sample calculation of the PLRCI and PLRCSI values for station 1 during the AM peak period (Table 5.6) is provided as follows:

Mean recurring congestion probability = Pi = 8.6 %

Mean recurring congestion index = Mi = 27.8 %

Mean recurring congestion severity index = s_i = 10.1 mph

PLRCI = Pi * Mi = 0.086 * 0.278 = 239×10^{-4}



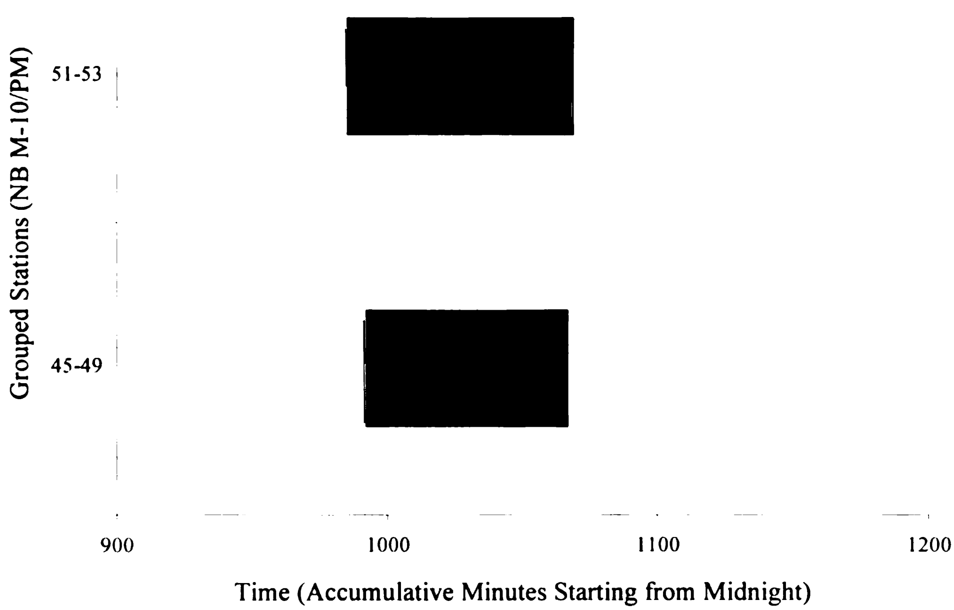


Figure 5.7 The M-10 Freeway Recurring Congestion Start Time and Duration Groups.

Figure 5.8 The I-94 Freeway Recurring Congestion Start Time and Duration Groups.

Table 5.7 Probabilistic Location Recurring Congestion Indices (WB I-94).

Station I.D.	P_i[1] (%)		M_i[2] (%)		s_i[3] (mph)		PLRCI[4] x 10^{-4}		PLRCSI[5] (mph) x 10^{-2}	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
1	8.6	0.0	27.8	0.0	10.1	0.0	239	0	86	0
2	15.6	1.9	28.3	6.8	12.1	9.5	441	13	188	18
3	19.0	0.0	29.7	0.0	8.4	0.0	566	0	160	0
4	27.0	2.5	31.8	7.8	12.1	20.2	860	19	328	51
5	21.3	2.4	34.0	11.0	10.5	20.2	726	26	223	48
6	21.3	2.4	34.0	11.0	10.5	20.2	726	26	223	48
7	15.6	2.3	36.2	14.2	8.8	20.2	566	32	138	46
8	15.6	2.3	36.2	14.2	8.8	20.2	566	32	138	46
9	23.8	4.4	36.8	18.4	9.4	18.2	875	82	224	81
10	28.0	3.6	34.4	35.6	8.2	19.3	963	129	228	70
11	14.3	3.6	39.9	44.3	6.4	20.5	570	161	91	75
12	22.0	0.0	38.3	0.0	7.5	0.0	843	0	164	0
13	14.3	0.0	50.0	0.0	8.1	0.0	714	0	116	0
14	38.6	3.4	24.8	10.7	6.9	15.9	958	36	265	54
15	53.1	1.6	25.8	11.1	8.0	16.9	1367	18	424	27
16	62.3	3.3	25.8	11.7	7.1	16.4	1605	39	440	55
17	62.3	3.3	25.8	11.7	7.1	16.4	1605	39	440	55
18	60.0	3.7	24.5	17.9	6.4	14.8	1471	66	382	55
19	96.0	7.5	33.0	15.6	9.8	16.6	3165	118	942	125
20	58.0	3.7	35.6	22.2	9.8	19.2	2063	82	566	71
21	88.5	25.8	46.9	24.3	14.1	13.6	4144	628	1250	350
22	50.0	18.2	24.8	11.1	6.6	7.1	1241	201	330	130

Note:
1 P_i = Probability of recurring congestion at location i (%).
2 M_i = Mean recurring congestion index at station i (%).
3 s_i = Mean recurring congestion severity at station i (mph).
4 PLRCI = Probabilistic Location Recurring Congestion Index (dimensionless).
5 PLRCSI = Probabilistic Location Recurring Congestion Severity Index (mph).

Table 5.8 Probabilistic Location Recurring Congestion Indices (EB I-94).

Station I.D.	P_I[1] (%)		M_i[2] (%)		s_i[3] (mph)		PLRCI[4] x 10^{-4}		PLRCSI[5] (mph) x 10^{-2}	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
23	0.0	12.5	0.0	10.6	0.0	7.1	0	133	0	89
24	0.0	29.3	0.0	26.2	0.0	9.5	0	768	0	278
25	0.0	8.3	0.0	20.6	0.0	2.6	0	172	0	22
26	0.0	8.3	0.0	20.6	0.0	2.6	0	172	0	22
27	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
28	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
29	0.0	17.9	0.0	40.1	0.0	4.1	0	718	0	73
30	0.0	3.0	0.0	19.3	0.0	8.8	0	58	0	26
31	0.0	3.0	0.0	19.3	0.0	8.8	0	58	0	26
32	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
33	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
34	0.0	2.7	0.0	15.7	0.0	7.4	0	42	0	20
35	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
36	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
37	0.0	1.6	0.0	25.9	0.0	3.9	0	41	0	6
38	0.0	6.7	0.0	18.9	0.0	8.2	0	126	0	55
39	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
40	0.0	3.2	0.0	34.7	0.0	7.7	0	110	0	24
41	0.0	8.6	0.0	31.9	0.0	10.9	0	273	0	94
42	0.0	6.7	0.0	29.6	0.0	9.1	0	197	0	60
43	0.0	4.8	0.0	27.3	0.0	7.2	0	130	0	34
44	0.0	13.3	0.0	25.8	0.0	7.6	0	344	0	101

Note:
1 P_i = Probability of recurring congestion at location i (%).
2 M_i = Mean recurring congestion index at station i (%).
3 s_i = Mean recurring congestion severity at station i (mph).
4 PLRCI = Probabilistic Location Recurring Congestion Index (dimensionless).
5 PLRCSI = Probabilistic Location Recurring Congestion Severity Index (mph).

Table 5.9 Probabilistic Location Recurring Congestion Indices (NB M-10).

Station I.D.	P_i[1] (%)		M_i[2] (%)		s_i[3] (mph)		PLRCI[4] x 10^{-4}		PLRCSI[5] (mph) x 10^{-2}	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
45	0.0	34.0	0.0	29.6	0.0	11.9	0	1006	0	403
46	0.0	38.1	0.0	28.6	0.0	9.2	0	1091	0	349
47	0.0	42.0	0.0	27.1	0.0	8.6	0	1140	0	361
48	0.0	44.8	0.0	25.9	0.0	9.5	0	1162	0	426
49	0.0	47.6	0.0	31.8	0.0	6.7	0	1515	0	321
50	0.0	22.9	0.0	33.5	0.0	7.1	0	765	0	163
51	0.0	22.9	0.0	33.5	0.0	7.1	0	765	0	163
52	0.0	24.3	0.0	29.4	0.0	5.2	0	713	0	125
53	0.0	18.3	0.0	20.1	0.0	5.4	0	369	0	98
54	0.0	5.8	0.0	13.0	0.0	6.6	0	75	0	38
55	9.1	4.8	18.9	17.6	10.0	2.1	171	84	91	10
56	0.0	5.7	0.0	13.1	0.0	8.8	0	75	0	50
57	0.0	5.7	0.0	13.1	0.0	8.8	0	75	0	50
58	0.0	5.7	0.0	13.1	0.0	8.8	0	75	0	50
59	0.0	18.2	0.0	16.6	0.0	5.6	0	303	0	102
60	2.9	9.1	22.5	20.4	17.8	8.1	66	185	52	73
61	0.0	8.3	0.0	26.9	0.0	7.6	0	224	0	63
62	1.8	3.2	29.1	19.9	16.9	11.8	51	64	30	38
63	2.6	6.7	36.9	24.2	21.1	9.3	95	161	54	62
64	2.9	2.2	21.7	14.4	16.8	13.0	62	31	48	28
65	0.0	0.0	21.7	0.0	0.0	0.0	0	0	0	0
66	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
67	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0
68	0.0	3.2	0.0	17.1	0.0	23.0	0	55	0	74

Note:
1 P_i = Probability of recurring congestion at location i (%).
2 M_i = Mean recurring congestion index at station i (%).
3 s_i = Mean recurring congestion severity at station i (mph).
4 PLRCI = Probabilistic Location Recurring Congestion Index (dimensionless).
5 PLRCSI = Probabilistic Location Recurring Congestion Severity Index (mph).

Table 5.10 Probabilistic Location Recurring Congestion Indices (SB M-10).

Station I.D.	P_i[1] (%)		M_i[2] (%)		s_i[3] (mph)		PLRCI[4] x 10^{-4}		PLRCSI[5] (mph) x 10^{-2}	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
69	5.9	5.3	15.9	35.2	10.2	23.2	94	185	60	122
70	12.5	0.0	6.9	0.0	5.9	0.0	86	0	74	0
71	58.6	0.0	30.4	0.0	8.1	0.0	1780	0	474	0
72	64.5	0.0	31.8	0.0	8.4	0.0	2052	0	543	0
73	21.7	15.4	12.2	11.1	5.0	6.1	266	170	109	93
74	37.1	0.0	28.3	0.0	7.5	0.0	1052	0	279	0
75	44.3	1.4	30.2	8.3	8.7	6.2	1338	12	386	9
76	46.3	2.7	30.0	15.8	8.6	15.8	1386	43	397	43
77	55.6	25.0	17.8	15.7	8.5	10.6	991	393	475	264
78	47.1	1.4	30.0	41.9	7.3	16.5	1410	59	342	23
79	23.9	4.1	28.3	43.1	3.9	13.7	676	177	93	56
80	37.5	0.0	30.9	0.0	2.6	0.0	1161	0	98	0
81	20.0	0.0	14.8	0.0	3.7	0.0	296	0	75	0
82	5.7	0.0	10.0	0.0	6.5	0.0	57	0	37	0
83	4.3	0.0	10.6	0.0	6.3	0.0	45	0	27	0
84	4.2	0.0	16.5	0.0	9.7	0.0	69	0	40	0
85	7.1	3.4	22.1	10.4	7.5	13.2	158	36	53	46
86	2.9	2.8	22.5	10.4	8.5	13.0	64	29	24	36
87	2.8	1.4	18.1	18.3	8.0	20.6	50	25	22	28
88	2.0	1.9	25.0	22.2	4.5	23.6	49	41	9	44
89	15.7	0.0	29.1	0.0	6.9	0.0	457	0	108	0
90	23.1	0.0	26.6	0.0	10.2	0.0	614	0	235	0
91	24.2	1.4	33.3	7.1	9.2	14.3	807	10	223	21

Note:
1 P_i = Probability of recurring congestion at location i (%).
2 M_i = Mean recurring congestion index at station i (%).
3 s_i = Mean recurring congestion severity at station i (mph).
4 PLRCI = Probabilistic Location Recurring Congestion Index (dimensionless).
5 PLRCSI = Probabilistic Location Recurring Congestion Severity Index (mph).

PLRCSI = Pi * si = 0.086 * 10.1 = 86 x 10^{-4} mph

The PLRCI is an indicator of the frequency of recurring congestion while PLRCSI is an indicator of its severity. For example, stations 61 and 63 (Table 5.9) have almost the same recurring congestion severity value during the PM peak period (63 and 62, respectively) but station 61 is more congested than station 63 by a factor of two. This situation indicates that when recurring congestion occurs at stations 61 and 63 during the PM peak period, the traffic experiences almost the same speed drop below the 35 mph speed threshold, but the average volume of congested vehicles is twice as great for station 61 compared to station 63.

The PLRCI and PLRCSI quantify congestion at a specific location. Thus, these measures do not capture the extent of recurring congestion along a freeway segment or compare the levels of recurring congestion on different freeway segments. For these purposes, PFRCI and PFRCSI are developed next.

5.5.2 Probabilistic Freeway Recurring Congestion Indices

The Probabilistic Freeway Recurring Congestion and Severity Indices (PFRCI and PFRCSI) are indicators of the extent of freeway recurring congestion and its severity along a freeway segment. Table 5.11 shows PFRCI and PFRCSI values for the study segments.

Table 5.11 shows that even though both the WB I-94 and SB M-10 freeway segments are congested during the AM peak, I-94 is more congested than M-10 by a factor of 2. This ratio also applies to congestion severity on these two freeway segments during the AM peak period. This an indication that the level of congestion on WB I-94 during the AM peak period is twice as much as on SB M-10.

Table 5.11 Probabilistic Freeway Recurring Congestion Indices.

Freeway	K[1]	PFRCI[2] x 10^{-4}		PFRCSI[3] (mph) X 10^{-2}	
		AM	PM	AM	PM
EB I-94	21	0	151	0	39
WB I-94	22	1240	77	347	64
SB M-10	22	703	49	195	32
NB M-10	23	21	423	13	122

Note: 1 k = Total number of data collection stations.
2 PFRCI = Probabilistic Freeway Recurring Congestion Index (dimensionless).
3 PFRCSI = Probabilistic Freeway Recurring Congestion Severity Index (mph).

The table also shows the NB M-10 freeway segment is the most congested segment during the PM peak period. Even though this congestion is less than half of what is experienced on the SB M-10 freeway segment during the AM peak period, its severity is relatively high.

5.5.3 Freeway System Recurring Congestion Measure

The Freeway System Recurring Congestion Measure (FSRCM) is a measure of the average daily traffic delay over a freeway system (vehicle-hours). Vehicle delay (vehicle-hours) values were calculated for the freeway study stations (based on Equation 8 in Chapter 4). Tables 5.12 through 5.15 summarize the results. The maximum values of the vehicle delay, excluding the odd stations 19-21 (WB I-94) and 71-72 (SB M-10), range from 223 to 246 vehicle-hours.

A summary of the study freeway segments' vehicle delay values is presented in Table 5.16. The FSRCM of the freeway system is calculated as the summation of the vehicle delays shown in this Table. Accordingly, the study FSRCM is calculated as 5,728 vehicle-hours during both the AM and PM peak periods (12/96-7/97).

5.6 Summary

A freeway recurring congestion speed threshold was defined based on statistical analysis of the recurring congestion index means at three selected speed thresholds. The data availability and probability of recurring congestion at each data collection location were also presented.

The start time and duration of recurring congestion at each study segment location were identified. The locations that have statistically similar start time and duration were grouped together to produce models that can be used in future data collection strategies.

Table 5.12 Vehicle Delay (WB I-94).

Station I.D.	P_I[1] (%)		V_{ci}[2] (vehicles)		s_i[3] (mph)		Vehicle Delay (vehicle-hours)	
	AM	AM	AM	AM	PM	PM	AM	PM
1	8.6	0.0	12323	0	10.1	0.0	NA	NA
2	15.6	1.9	27839	776	12.1	9.5	21.8	0.1
3	19.0	0.0	38346	0	8.4	0.0	22.0	0.0
4	27.0	2.5	46035	697	12.1	20.2	62.8	0.2
5	21.3	2.4	39215	1186	10.5	20.2	34.0	0.4
6	21.3	2.4	39215	1186	10.5	20.2	34.0	0.4
7	15.6	2.3	32395	1674	8.8	20.2	16.2	0.5
8	15.6	2.3	32395	1674	8.8	20.2	16.2	0.5
9	23.8	4.4	59082	3096	9.4	18.2	49.3	1.4
10	28.0	3.6	79191	5860	8.2	19.3	64.2	2.5
11	14.3	3.6	50688	8861	6.4	20.5	15.3	4.4
12	22.0	0.0	77744	0	7.5	0.0	44.2	0.0
13	14.3	0.0	62702	0	8.1	0.0	25.9	0.0
14	38.6	3.4	77503	2436	6.9	15.9	69.5	0.7
15	53.1	1.6	127303	1372	8.0	16.9	190.6	0.2
16	62.3	3.3	163998	2836	7.1	16.4	245.8	0.8
17	62.3	3.3	163998	2836	7.1	16.4	245.8	0.8
18	60.0	3.7	143002	5313	6.4	14.8	181.6	1.4
19	96.0	7.5	289212	8067	9.8	16.6	1029.8	5.2
20	58.0	3.7	189223	6564	9.8	19.2	403.8	2.8
21	88.5	25.8	174285	27649	14.1	13.6	994.0	43.1
22	50.0	18.2	18365	3083	6.6	7.1	NA	NA

Note: 1 Probability of recurring congestion (%)
2 V_{ci} = Total volume of vehicles with speeds less than or equal to the 35 mph speed threshold at location i.
3 s_i = Mean recurring congestion severity at station i (mph).

Table 5.13 Vehicle Delay (EB I-94).

Station I.D.	P_I[1] (%)		V_{ci}[2] (vehicles)		s_i[3] (mph)		Vehicle Delay (vehicle-hours)	
	AM	AM	AM	AM	PM	PM	AM	PM
23	0.0	12.5	0	2199	0.0	7.1	NA	NA
24	0.0	29.3	0	87799	0.0	9.5	0.0	91.0
25	0.0	8.3	0	4349	0.0	2.6	0.0	0.3
26	0.0	8.3	0	4349	0.0	2.6	0.0	0.3
27	0.0	0.0	0	0	0.0	0.0	0.0	0.0
28	0.0	0.0	0	0	0.0	0.0	0.0	0.0
29	0.0	17.9	0	103606	0.0	4.1	0.0	23.3
30	0.0	3.0	0	7316	0.0	8.8	0.0	0.7
31	0.0	3.0	0	7316	0.0	8.8	0.0	0.7
32	0.0	0.0	0	0	0.0	0.0	0.0	0.0
33	0.0	0.0	0	0	0.0	0.0	0.0	0.0
34	0.0	2.7	0	2701	0.0	7.4	0.0	0.2
35	0.0	0.0	0	0	0.0	0.0	0.0	0.0
36	0.0	0.0	0	0	0.0	0.0	0.0	0.0
37	0.0	1.6	0	4785	0.0	3.9	0.0	0.1
38	0.0	6.7	0	6751	0.0	8.2	0.0	1.3
39	0.0	0.0	0	0	0.0	0.0	0.0	0.0
40	0.0	3.2	0	11083	0.0	7.7	0.0	0.9
41	0.0	8.6	0	15632	0.0	10.9	0.0	5.8
42	0.0	6.7	0	14478	0.0	9.1	0.0	3.2
43	0.0	4.8	0	13323	0.0	7.2	0.0	1.6
44	0.0	13.3	0	36564	0.0	7.6	NA	NA

Note: 1 Probability of recurring congestion (%)
2 V_{ci} = Total volume of vehicles with speeds less than or equal to the 35 mph speed threshold at location i.
3 s_i = Mean recurring congestion severity at station i (mph).

Table 5.14 Vehicle Delay (NB M-10).

Station I.D.	P_I[1] (%)		V_{ci}[2] (vehicles)		s_i[3] (mph)		Vehicle Delay (vehicle-hours)	
	AM	AM	AM	AM	PM	PM	AM	PM
45	0.0	34.0	0	85432	0.0	11.9	NA	NA
46	0.0	38.1	0	120161	0.0	9.2	0.0	154.7
47	0.0	42.0	0	115680	0.0	8.6	0.0	150.9
48	0.0	44.8	0	139908	0.0	9.5	0.0	222.3
49	0.0	47.6	0	139607	0.0	6.7	0.0	151.0
50	0.0	22.9	0	102846	0.0	7.1	0.0	57.3
51	0.0	22.9	0	102846	0.0	7.1	0.0	57.3
52	0.0	24.3	0	105023	0.0	5.2	0.0	42.0
53	0.0	18.3	0	44671	0.0	5.4	0.0	14.1
54	0.0	5.8	0	11293	0.0	6.6	0.0	1.5
55	9.1	4.8	2145	3175	10.0	2.1	0.7	0.1
56	0.0	5.7	0	10858	0.0	8.8	0.0	2.0
57	0.0	5.7	0	10858	0.0	8.8	0.0	2.0
58	0.0	5.7	0	10858	0.0	8.8	0.0	2.0
59	0.0	18.2	0	32991	0.0	5.6	0.0	10.9
60	2.9	9.1	1771	15869	17.8	8.1	0.5	4.1
61	0.0	8.3	0	5680	0.0	7.6	0.0	1.3
62	1.8	3.2	2056	7567	16.9	11.8	0.3	1.2
63	2.6	6.7	2749	13579	21.1	9.3	1.0	3.1
64	2.9	2.2	2427	3180	16.8	13.0	0.6	0.4
65	0.0	0.0	0	0	0.0	0.0	0.0	0.0
66	0.0	0.0	0	0	0.0	0.0	0.0	0.0
67	0.0	0.0	0	0	0.0	0.0	0.0	0.0
68	0.0	3.2	0	2780	0.0	23.0	NA	NA

Note:
1 Probability of recurring congestion (%)
2 V_{ci} = Total volume of vehicles with speeds less than or equal to the 35 mph speed threshold at location i.
3 s_i = Mean recurring congestion severity at station i (mph).

Table 5.15 Vehicle Delay (SB M-10).

Station I.D.	P_I[1] (%)		V_{ci}[2] (vehicles)		s_i[3] (mph)		Vehicle Delay (vehicle-hours)	
	AM	AM	AM	AM	PM	PM	AM	PM
69	5.9	5.3	2369	3620	10.2	23.2	NA	NA
70	12.5	0.0	2546	0	5.9	0.0	0.6	0.0
71	58.6	0.0	153257	0	8.1	0.0	256.9	0.0
72	64.5	0.0	216608	0	8.4	0.0	421.7	0.0
73	21.7	15.4	5941	1676	5.0	6.1	2.1	0.5
74	37.1	0.0	116245	0	7.5	0.0	112.3	0.0
75	44.3	1.4	129865	1035	8.7	6.2	181.4	0.0
76	46.3	2.7	155459	4206	8.6	15.8	222.6	0.9
77	55.6	25.0	31138	15212	8.5	10.6	53.3	15.6
78	47.1	1.4	168267	6034	7.3	16.5	197.9	0.7
79	23.9	4.1	87104	19313	3.9	13.7	24.8	4.9
80	37.5	0.0	18256	0	2.6	0.0	5.3	0.0
81	20.0	0.0	5753	0	3.7	0.0	1.3	0.0
82	5.7	0.0	8011	0	6.5	0.0	1.0	0.0
83	4.3	0.0	6614	0	6.3	0.0	0.6	0.0
84	4.2	0.0	7412	0	9.7	0.0	1.1	0.0
85	7.1	3.4	8706	1512	7.5	13.2	1.6	0.3
86	2.9	2.8	5969	3000	8.5	13.0	0.5	0.5
87	2.8	1.4	7539	2769	8.0	20.6	0.6	0.5
88	2.0	1.9	2275	3301	4.5	23.6	0.1	1.2
89	15.7	0.0	68393	0	6.9	0.0	25.1	0.0
90	23.1	0.0	62907	0	10.2	0.0	56.7	0.0
91	24.2	1.4	84712	1038	9.2	14.3	NA	NA

Note: 1 Probability of recurring congestion (%)
2 V_{ci} = Total volume of vehicles with speeds less than or equal to the 35 mph speed threshold at location i.
3 s_i = Mean recurring congestion severity at station i (mph).

Table 5.16 Study Segments Vehicle Delay.

Freeway	k[1]	Vehicle Delay (vehicle-hours)	
		AM	PM
EB I-94	21	0	129
WB I-94	22	3367	65
SB M-10	22	1567	25
NB M-10	23	3	572

Note: 1 k = Total number of data collection stations.

The probabilistic recurring congestion location and freeway indices were applied to the study segments that allowed numerical comparisons of the recurring congestion levels on the different study segments. Recurring congestion patterns were also identified in an urban freeway traffic environment.

Average daily freeway traffic delay (vehicle-hours) due to recurring congestion was also quantified on a location, segment, and system bases through calculating the FSRCM values. Comparisons between the recurring congestion level on the study segments during the AM and PM peak periods were performed.

Chapter 6

SENSITIVITY ANALYSIS AND VALIDATION

The previous chapter presented bases to establish a sampling plan for future data collection to measure congestion. This chapter focuses on testing the reliability of the proposed plan. This analysis is used to establish a sampling plan that minimizes the number of locations and frequency of data collection required to obtain a reliable congestion measure.

The analyses in the previous chapter were based on a common database that combined 8 months of data (December 1996 – July 1997). In this chapter, the differences in the congestion measure over days of the week and seasons of the year are studied. The developed models are then validated using one month of data (August 1997). The congestion values are also compared to the CALTRANS methodology values. Finally, a comparison between recurring and nonrecurring congestion values is conducted.

6.1 Weekday Variations

Tables 6.1 through 6.3 show total number of days for which data are available and the number of congested days on the three most congested freeway segments (WB I-94 AM, NB M-10 PM, and SB M-10 AM, respectively) distributed by weekday. Only one station (station 19) out of 69 stations has a sample size of five or more congested days on each weekday. This was not considered a sufficient sample size to conduct an analysis of

Table 6.1 Weekday Data Distribution (WB I-94 AM Peak Period).

Station I.D.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays	
	Total	Cong[1]	Total	Cong	Total	Cong	Total	Cong	Total	Cong
1	6	0	8	1	6	2	8	0	7	0
2	9	1	9	1	8	2	11	3	8	0
3	9	1	7	2	7	2	11	3	8	0
4	10	1	7	2	5	2	8	4	7	1
5	NA[2]	NA	NA	NA	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7	7	0	6	0	7	2	6	2	6	1
8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9	10	3	8	2	7	2	9	2	8	1
10	12	3	9	2	9	4	11	4	9	1
11	12	2	9	1	9	2	11	2	8	0
12	11	1	11	3	10	3	8	3	10	1
13	9	1	11	1	10	2	9	2	10	1
14	9	5	12	4	9	4	8	2	6	2
15	10	7	11	6	10	6	9	3	9	4
16	12	9	11	7	8	7	11	6	11	4
17	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
18	13	8	10	7	9	6	9	6	9	3
19	12	11	10	10	9	9	10	9	9	9
20	12	6	10	6	9	7	10	6	9	4
21	6	5	6	5	4	4	6	5	4	4
22	NA	NA	3	0	2	2	1	1	2	1

Note: 1 Recurring Congestion.
2 Data are not available because detector is not functioning.

Table 6.2 Weekday Data Distribution (NB M-10 PM Peak Period).

Station I.D.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays	
	Total	Cong[1]	Total	Cong	Total	Cong	Total	Cong	Total	Cong
45	9	3	11	4	10	5	10	3	10	2
46	14	4	14	6	13	5	12	5	10	4
47	12	4	11	5	10	4	9	4	8	4
48	10	4	13	5	11	6	12	6	12	5
49	7	3	10	5	9	4	8	4	8	4
50	NA[2]	NA	NA	NA	NA	NA	NA	NA	NA	NA
51	14	3	15	3	14	4	14	4	13	2
52	14	2	15	3	14	5	14	5	13	2
53	12	2	13	3	11	2	12	2	12	2
54	14	0	15	0	13	2	14	1	13	2
55	5	0	5	0	3	0	2	0	6	1
56	14	0	15	1	14	1	14	1	13	1
57	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
58	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
59	10	0	12	2	11	5	11	0	11	1
60	8	0	10	1	8	2	10	0	8	1
61	3	0	2	1	2	0	3	0	2	0
62	12	0	13	1	11	0	13	0	13	1
63	10	0	10	1	8	0	9	0	9	2
64	10	0	10	0	9	0	9	0	9	1
65	2	0	1	0	NA	NA	1	0	1	0
66	2	0	2	0	1	0	2	0	1	0
67	2	0	2	0	1	0	2	0	1	0
68	6	0	6	0	7	0	6	0	6	1

Note: 1 Recurring Congestion.
2 Data are not available because detector is not functioning.

Table 6.3 Weekday Data Distribution (SB M-10 AM Peak Period).

Station I.D.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays	
	Total	Cong[1]	Total	Cong	Total	Cong	Total	Cong	Total	Cong
69	2	0	4	1	4	0	4	0	3	0
70	2	0	4	1	4	1	4	0	2	0
71	10	3	12	10	13	11	14	7	9	3
72	12	6	13	12	12	10	15	9	10	3
73	10	2	9	5	8	1	11	1	8	1
74	14	3	14	7	13	8	16	6	13	2
75	10	2	12	8	12	7	15	6	12	4
76	13	5	15	9	14	9	15	6	10	2
77	3	2	5	2	3	3	4	1	3	2
78	14	3	15	9	14	9	15	8	10	3
79	14	2	15	6	14	5	14	3	10	0
80	NA[2]	NA	3	0	2	1	2	2	1	0
81	2	1	2	0	2	1	2	0	2	0
82	13	0	15	3	14	0	15	1	13	0
83	13	0	15	2	14	0	15	1	13	0
84	14	0	15	2	14	0	16	1	13	0
85	6	1	6	1	5	0	6	0	5	0
86	13	0	15	1	13	0	16	1	13	0
87	14	0	15	1	14	0	16	1	13	0
88	8	0	11	0	10	0	12	1	10	0
89	14	2	15	4	14	2	15	3	12	0
90	10	1	13	3	14	4	16	5	12	2
91	11	2	13	3	14	4	16	5	12	2

Note: 1 Recurring Congestion.
2 Data are not available because detector is not functioning.

weekday congestion variation on a station by station level.

Table 6.4 shows a summary of the total data collection days and congested days on a segment basis. The percentage of congested days to total available days varies from 11 to 49 percent for the different weekdays and freeway segments. The table also shows that this percentage varies from one weekday to another for the same freeway segment and from one freeway segment to another on the same weekday.

Weekday Bonferroni multiple comparisons of the mean values of the recurring congestion indices (Mi) are presented in Table 6.5. These results show that:

1. The mean value of the congestion index (Mi) is not statistically different at a 5% significance level during the AM peak periods on Mondays and Tuesdays,
2. The mean value of the congestion index (Mi) is not statistically different at a 5% significance level during the AM peak periods on Wednesdays and Thursdays,
3. The mean value of the congestion index (Mi) during the AM peak periods on Fridays is also not statistically different at a 5% significance level than on Mondays and Tuesdays,
4. The mean value of the congestion index (Mi) during the AM peak periods on Fridays is not statistically different at a 5% significance level than on Wednesdays and Thursdays except for SB M-10, and
5. The mean value of the congestion index (Mi) is not statistically different at a 5% significance level during the PM peak periods on all weekdays.

The above results indicate that a data collection plan should include either a Monday or Tuesday, a Wednesday or Thursday, and a Friday in order to estimate the

Table 6.4 Summary of Weekday Data Distribution.

Segment	Mondays	Tuesdays	Wednesdays	Thursdays	Fridays
	Total Days				
WB I-94 AM	169	158	138	156	140
NB M-10 PM	190	205	180	187	179
SB M-10 AM	222	256	241	274	209
	Congested Days				
WB I-94 AM	64	60	68	63	37
NB M-10 PM	25	41	45	35	36
SB M-10 AM	35	90	76	68	24
	% Congestion				
WB I-94 AM	38	38	49	40	26
NB M-10 PM	13	20	25	19	20
SB M-10 AM	16	35	32	25	11

Table 6.5 Weekday Comparison of Recurring Congestion Index (M_i).

Weekday (I)	Weekday (J)	WB I-94 AM			SB M-10 AM			NB M-10 PM		
		Mean Diff[1] (I-J)	Std. Err.[2]	P-value[3]	Mean Diff (I-J)	Std. Err.	P-value	Mean Diff (I-J)	Std. Err.	P-value
Mon	Tue	-0.02	0.03	1.00	-0.03	0.03	1.00	0.08	0.05	0.68
	Wed	-0.12*	0.03	0.00	-0.12*	0.03	0.00	0.04	0.05	1.00
	Thu	-0.13*	0.03	0.00	-0.12*	0.03	0.00	0.00	0.05	1.00
	Fri	-0.07	0.04	0.51	0.01	0.04	1.00	0.08	0.05	1.00
Tue	Mon	0.02	0.03	1.00	0.03	0.03	1.00	-0.08	0.05	0.68
	Wed	-0.10*	0.03	0.01	-0.09*	0.02	0.00	-0.04	0.04	1.00
	Thu	-0.11*	0.03	0.00	-0.09*	0.02	0.00	-0.08	0.04	0.50
	Fri	-0.05	0.04	1.00	0.04	0.03	1.00	-0.01	0.04	1.00
Wed	Mon	0.12*	0.03	0.00	0.12*	0.03	0.00	-0.04	0.05	1.00
	Tue	0.10*	0.03	0.01	0.09*	0.02	0.00	0.04	0.04	1.00
	Thu	-0.02	0.03	1.00	0.00	0.02	1.00	-0.04	0.04	1.00
	Fri	0.05	0.04	1.00	0.13*	0.03	0.00	0.03	0.04	1.00
Thu	Mon	0.13*	0.03	0.00	0.12*	0.03	0.00	0.00	0.05	1.00
	Tue	0.11*	0.03	0.00	0.09*	0.02	0.00	0.08	0.04	0.50
	Wed	0.02	0.03	1.00	0.00	0.02	1.00	0.04	0.04	1.00
	Fri	0.06	0.04	0.90	0.13*	0.04	0.00	0.07	0.04	0.88
Fr	Mon	0.07	0.04	0.51	-0.01	0.04	1.00	-0.08	0.05	1.00
	Tue	0.05	0.04	1.00	-0.04	0.03	1.00	0.01	0.04	1.00
	Wed	-0.05	0.04	1.00	-0.13*	0.03	0.00	-0.03	0.04	1.00
	Thu	-0.06	0.04	0.90	-0.13*	0.04	0.00	-0.07	0.04	0.88

Note:
1 Difference between mean Mi on weekdays I and J.
2 Standard error between mean Mi on weekdays I and J.
3 P-value = Probability of (t-statistic > t-observed) assuming that the observed means are statistically equal at the corresponding weekdays.
* The mean difference of Mi is significant at the 0.05 level.

recurring congestion index on a freeway segment during the AM peak period. Collecting data on any weekday is sufficient to estimate the recurring congestion measure the during the PM peak period. The result from this analysis can be used to reduce the size of the data sample in future data collection efforts. Analysis of seasonal variations in the recurring congestion index is provided in the next section.

6.2 Seasonal Variations

Tables 6.6 through 6.8 show total and congested days on the three most congested freeway segments (WB I-94 AM, NB M-10 PM, and SB M-10 AM, respectively) distributed on the seasons (Spring/Summer and Fall/Winter). The number of days on which data are available are fairly evenly distributed across the seasons, except for the WB I-94 freeway segment during the AM peak period (Spring/Summer to Fall/Winter ratio is approximately 2:3). The percentage of congested to total available days varies from 13 to 40 percent for the various seasons and congested freeway segments considered (Table 6.9). This percentage varies from one freeway segment to another, but the Fall/Winter value is always higher than the Spring/Summer one.

Table 6.10 shows the results of comparing the means of the recurring congestion indices (Mi) on the freeway segments during the seasons of the year at the 0.05 significant level. The results show that:

1. The mean congestion index (Mi) is not statistically different at a 5 % significance level on the WB I-94 freeway during the AM peak period for the Spring/Summer and Fall/Winter, and
2. The mean congestion index (Mi) is statistically different on both the NB and

Table 6.6 Seasonal Data Distribution (WB I-94 AM Peak Period).

Station I.D.	Spring/Summer		Fall/Winter	
	Total Days	Cong Days[1]	Total Days	Cong Days
1	10	0	25	3
2	17	0	28	7
3	14	0	28	8
4	7	0	30	10
5	NA[2]	NA	NA	NA
6	NA	NA	NA	NA
7	4	0	28	5
8	NA	NA	NA	NA
9	11	0	31	10
10	20	0	30	14
11	20	0	29	7
12	22	0	28	11
13	23	0	26	7
14	22	5	22	12
15	22	9	27	17
16	24	14	29	19
17	NA	NA	NA	NA
18	20	18	30	12
19	19	19	31	29
20	19	19	31	10
21	23	23	3	0
22	NA	0	8	4

Note: 1 Recurring Congestion.
2 Data are not available because detector is not functioning.

Table 6.7 Seasonal Data Distribution (NB M-10 PM Peak Period).

Station I.D.	Spring/Summer		Fall/Winter	
	Total Days	Cong Days[1]	Total Days	Cong. Days
45	21	4	29	13
46	32	7	31	16
47	21	7	29	14
48	26	7	32	19
49	9	1	33	19
50	NA[2]	NA	NA	NA
51	37	9	33	7
52	37	8	33	9
53	28	5	32	6
54	37	2	32	2
55	4	0	17	1
56	37	4	33	0
57	NA	NA	NA	NA
58	NA	NA	NA	NA
59	27	3	28	7
60	24	2	20	2
61	12	1	NA	NA
62	31	1	31	1
63	24	1	22	2
64	25	0	22	1
65	5	0	NA	NA
66	8	0	NA	NA
67	8	0	NA	NA
68	10	0	21	1

Note: 1 Recurring Congestion.
2 Data are not available because detector is not functioning.

Table 6.8 Seasonal Data Distribution (SB M-10 AM Peak Period).

Station I.D.	Spring/Summer		Fall/Winter	
	Total Days	Cong Days[1]	Total Days	Cong. Days
69	17	1	NA[2]	NA
70	16	2	NA	NA
71	27	11	31	23
72	32	17	30	23
73	17	4	29	6
74	38	7	32	19
75	31	7	30	20
76	34	7	33	24
77	18	10	NA	NA
78	35	4	33	28
79	35	4	32	12
80	NA	NA	8	3
81	10	2	NA	NA
82	38	2	32	2
83	38	2	32	1
84	38	2	34	1
85	28	2	NA	NA
86	36	1	34	1
87	38	2	34	0
88	18	0	33	1
89	37	11	33	0
90	31	14	34	1
91	32	15	34	1

Note: 1 Recurring Congestion.
2 Data are not available because detector is not functioning.

Table 6.9 Summary of Seasonal Data Distribution.

Segment	Spring/Summer	Fall/Winter
	Total Days	
WB I-94 AM	297	464
NB M-10 PM	463	478
SB M-10 AM	644	558
	Congested Days	
WB I-94 AM	107	185
NB M-10 PM	62	120
SB M-10 AM	127	166
	% Congestion	
WB I-94 AM	36	40
NB M-10 PM	13	25
SB M-10 AM	20	30

Table 6.10 Seasonal Comparisons of Recurring Congestion Index (M_i).

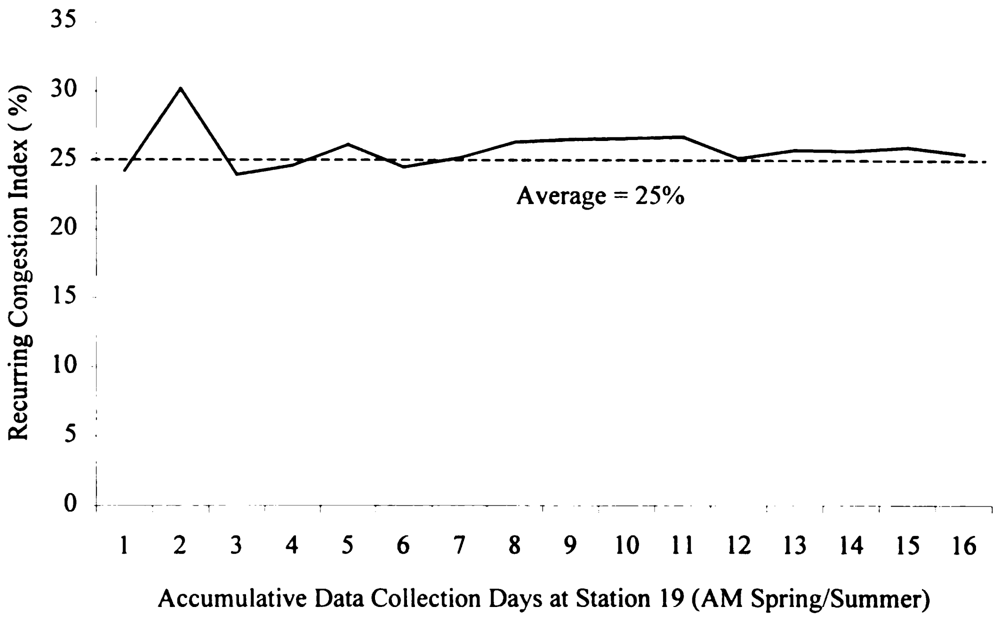
Season	WB I-94 AM			SB M-10 AM			NB M-10 PM		
	Mean Mi[1]	Std. Err.[2]	P-value[3]	Mean Mi	Std. Err.	P-value	Mean Mi	Std. Err.	P-value
Spring/Summer	0.296	0.015	0.066	0.244*	0.011	0.001	0.183*	0.012	0.000
Fall/Winter	0.336	0.014	0.066	0.306*	0.014	0.001	0.309*	0.018	0.000

Note:
1 Mean recurring congestion index during a season.
2 Standard error of the mean of Mi during a season.
3 P-value = Probability of (t-statistic > t-observed) assuming that the observed means are statistically equal at the two seasons.
* The mean of Mi is significantly different from season to season at the 0.05 level.

SB M-10 freeways during the AM and PM Spring/Summer and Fall/Winter peak periods.

Accordingly, to estimate the annual congestion values during the AM and PM peak periods on M-10 freeway, data collection is required during both the Spring/Summer and Fall/Winter seasons.

To study the stability of the average of the recurring congestion index (M) during the Spring/Summer and Fall/Winter season, stations 19 on WB I-94 and 72 on SB M-10 are selected during the AM peak period. Station 48 on NB M-10 is selected during the PM peak period. These stations were selected because they are the most frequently congested stations on the corresponding freeways and peak periods. Figure 6.1 shows the average M values for stations 19 and 72 during the AM peak period in the Spring/Summer season (values that are less than the 85th percentile values are excluded). By using ± 1% acceptable variation in the average M value, it noticed that this value



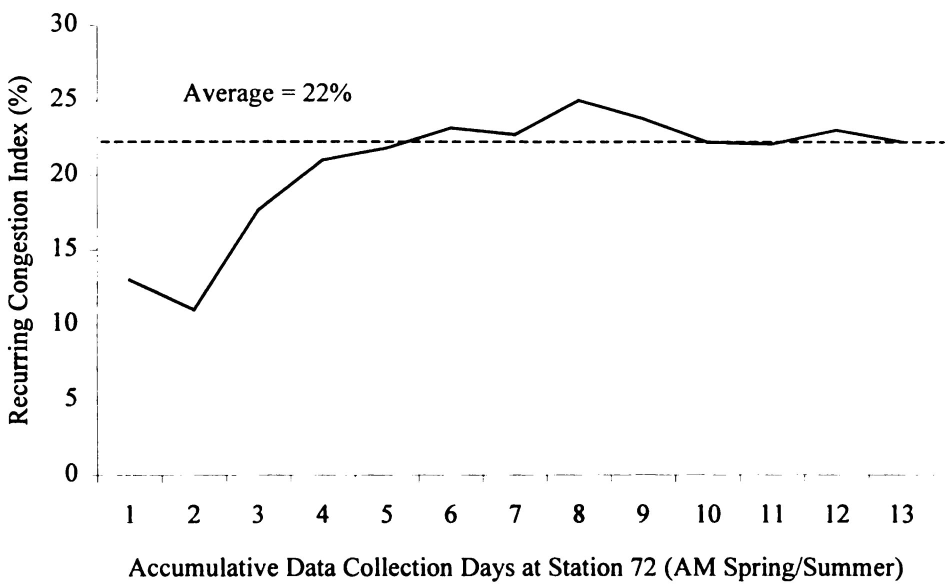


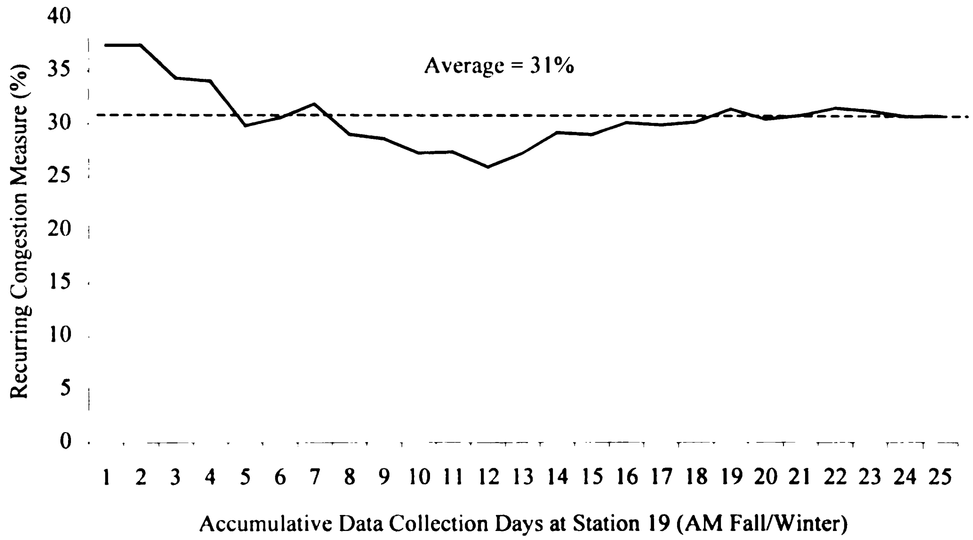
Figure 6.1 Recurring Congestion Index (M) at Stations 19 and 72 (AM Spring/Summer).

stabilizes after collecting 12 and 10 congested days at stations 19 and 72, respectively, during the AM peak periods in the Spring/Summer season, while it stabilized after collection 16 and 17 congested days, respectively, during the Fall/Winter season (Figure 6.2). On the other hand, the average M value starts to stabilize at station 48 after collecting 6 and 15 congested days during the PM peak periods in the Spring/Summer and Fall/Winter seasons, respectively (Figure 6.3).

6.3 Model Validation

To test the start time and duration of recurring congestion models that were presented in the previous chapter, the start time and duration of recurring congestion were calculated at each station during both the AM and PM peak. Then, data on 10 weekdays during the month of August 1997 were collected. A minimum sample size of two congested days was selected as a threshold to include a station in the model validation process. By using this threshold, stations 89, 90, and 91 (SB M-10 freeway segment) during the AM peak period were selected to test the model. Eight stations on the NB M-10 freeway segment satisfied this threshold, but were excluded because construction was taking place on this segment during August 1997.

Figure 6.4 shows the start time and duration of recurring congestion at stations 89-91 during (a) the 8-month (December 1996 – July 97) peak period, (b) the spring/summer (April – July 97) peak period, and (c) August 1997 AM peak period. The figure shows good agreement between the Spring/Summer and 8-month models, and the validation data (August 1997 data). The start and end time of the recurring congestion during the month of August 1997 lies within both models with a better fit with the Spring/Summer model. This pattern is expected because the spring/summer and



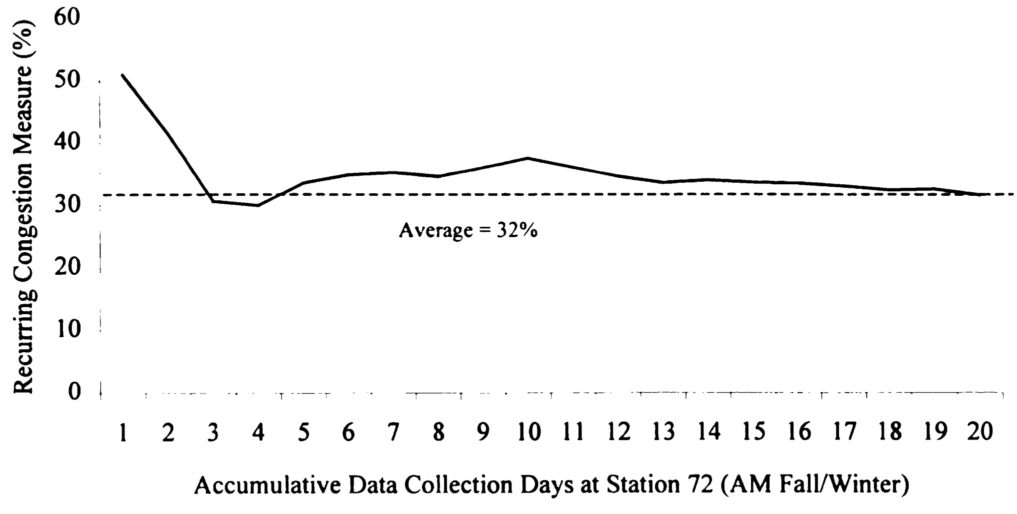
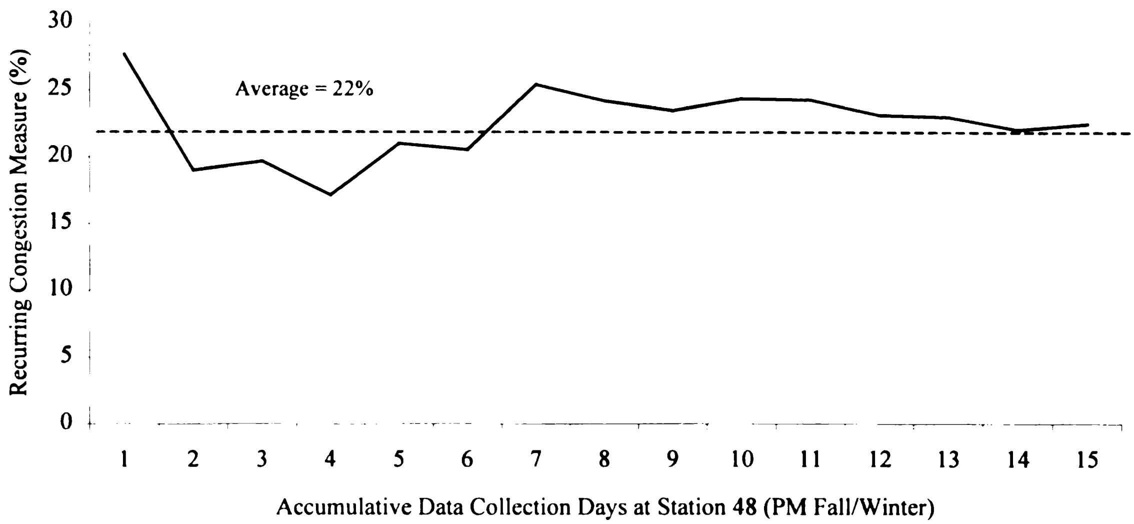


Figure 6.2 Recurring Congestion Index (M) at Stations 19 and 72 (AM Fall/Winter).



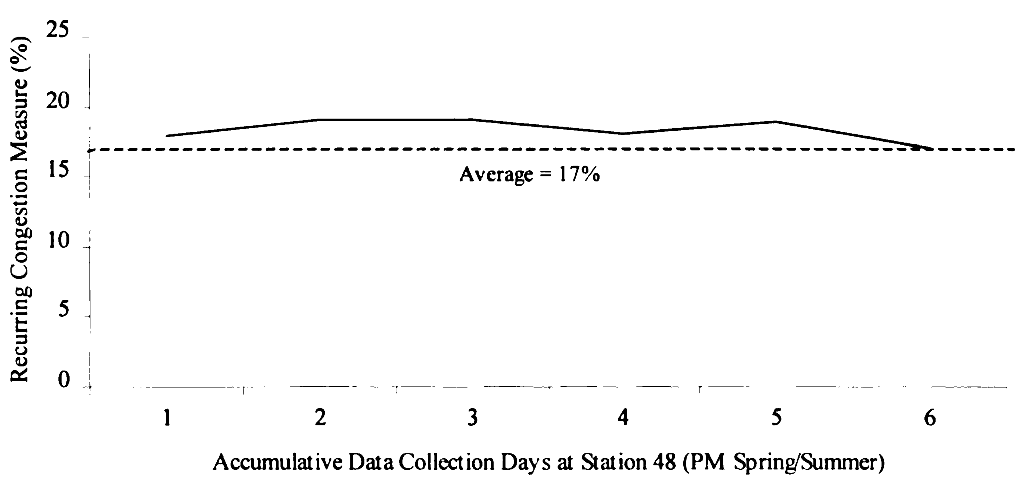


Figure 6.3 Recurring Congestion Index (M) at Station 48 (PM in both Seasons).

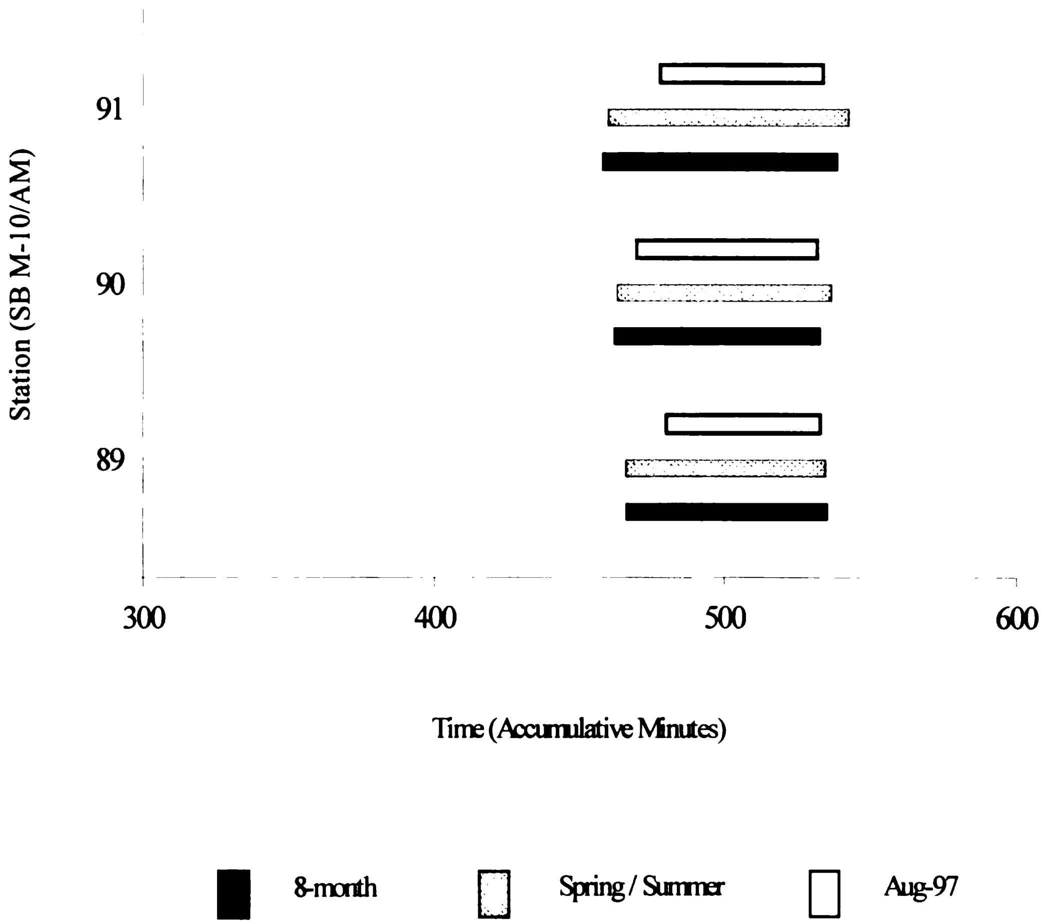


Figure 6.4 Recurring Congestion Start Time and Duration (SB M-10).

fall/winter season were found to be statistically different in the previous section. These results are encouraging, however, more extensive validation is recommended when additional data become available.

6.4 Comparison of Recurring and Nonrecurring Congestion

Total congestion is defined as the vehicle-minute of travel when traffic speed drops below the 35 mph threshold for one minute or more during a time interval. In other words, total congestion is the summation of short and long term congestion during a time interval.

Table 6.11 shows a comparison between a congestion index calculated based on 1-minute threshold as defined in Chapter 4 and the same index based on the 15-minute smoothing threshold adopted in this study. The table only includes the WB I-94 stations and days that experienced congestion. About 38% of the data collection days experienced only short-term congestion while the rest experienced at least one congested period lasting fifteen minutes or longer.

The total vehicle-minutes of delay occurring during the extended congestion periods is 18,244 minutes while short term congestion accounts for only 2,193 minutes. About 89% of the congestion duration is attributed to recurring congestion as defined in the study.

The percentage of traffic volume that experienced recurring and non-recurring congestion can be calculated as follows:

Traffic that experienced congestion = 100% x 4,193 x 363/30,784 x 363

= 14%

Table 6.11 Total and Recurring Congestion Comparison (WB I-94 AM).

Station I.D.	Total Days		Volume[1] (Vehicles)		Congested Volume[2] (Vehicles)		Total Congestion Duration[3] (Minutes)	
	TC[4]	RC[5]	TC	RC	TC	RC	TC	RC
1	6	3	23489	23503	2458	4108	239	203
2	8	5	23390	22383	3207	4785	423	400
3	8	6	26621	25951	4070	5549	472	482
4	16	8	23832	23088	3240	5337	794	680
7	12	4	29610	28059	3255	7408	509	398
9	21	9	27575	26522	3152	5745	944	757
10	22	14	27449	26919	4256	5657	1330	1147
11	19	7	32897	31058	3171	7241	816	693
12	20	10	32324	31142	4386	7522	1151	1003
13	19	7	32074	30051	3565	8957	923	860
14	24	13	30209	29783	3077	5011	982	871
15	28	19	31214	31216	4061	5352	1428	1283
16	31	25	31653	31576	4612	5178	1754	1590
18	36	21	33582	32649	3653	4905	1615	1284
19	36	36	31205	31205	6467	6203	3061	2938
20	36	21	34677	32930	4458	6614	2113	1865
21	14	12	30566	29469	7411	8410	1586	1554
22	7	4	34890	33838	3365	4591	297	236
Total	363	224					20437	18244
Weighted Average			30784	30129	4193	5992		

Note:
1 Average total volume of vehicles during 12:00 a.m.-11:59 p.m. 12/1996-5/1997 (vehicles per 12 hr).
2 Average congested volume of vehicles during 12:00 a.m.-11:59 a.m. 12/1996-5/1997 (vehicles per 12 hr).
3 Total duration of congestion during 12:00 a.m.-11:59 a.m. 12/1996-5/1997 (minutes).
4 Total congestion threshold of one minute or more.
5 Recurring congestion by using the study methodology.

Traffic that experienced recurring congestion = 100% x 5,992 x 224/30,784 x 363

= 12%

Traffic that experienced only non-recurring congestion = 14% - 12%

= 2%

In other words, it is estimated that about 86% of the congestion on the west bound I-94 freeway segment during the 12-hr time interval (from midnight to noon) is attributed to recurring congestion. In this study recurring congestion includes incident caused congestion that occurs between the start and end time of recurring congestion as defined for each station.

6.5 Comparison of Study and CALTRANS Methodologies

Table 6.12 shows the total recurring congestion duration and volume of the west bound I-94 freeway segment during the AM peak period between 12/1996-7/1997 by using the study and CALTRANS methodologies, respectively. The table shows that the CALTRANS methodology consistently underestimates the recurring congestion duration and volume at various stations in comparison with the study methodology. On the average, the CALTRANS methodology underestimates the recurring congestion duration and volume on this segment during the AM peak period by 11 and 12%, respectively.

These findings confirm earlier observations; namely the CALTRANS methodology is not capturing small variations or spikes in traffic speed. The above results show that the study methodology accounts for these variations better than the CALTRANS methodology. This feature is significant in selecting a congestion measure to evaluate a traffic management system because it captures most of the expected congestion reduction in the freeway system, especially due to short term duration

Table 6.12 FRSCM vs. CALTRANS Methodologies (WB I-94 AM).

Station I.D.	RC Days[1]	Total Recurring Congestion Duration (minutes)			Total Recurring Congestion Volume (vehicles)		
		FM[2]	CT[3]	%Diff[4]	FM	CT	%Diff[5]
1	3	203	194	-4	12323	11797	-4
2	7	452	452	0	27839	27839	0
3	8	543	515	-5	38346	36155	-6
4	10	728	694	-5	46035	43555	-5
7	5	431	420	-3	32395	31453	-3
9	10	881	821	-7	59082	54375	-8
10	14	1147	961	-16	79191	64610	-18
11	7	693	566	-18	50688	39516	-22
12	11	1040	926	-11	77744	67897	-13
13	7	860	705	-18	62702	49794	-21
14	17	1030	825	-20	77503	60888	-21
15	26	1606	1385	-14	127303	108191	-15
16	33	2015	1780	-12	163998	142922	-13
18	30	1769	1586	-10	143002	126658	-11
19	47	3830	3428	-10	286786	255810	-11
20	29	2567	2236	-13	189223	163510	-14
21	21	2499	2314	-7	161811	146147	-10
22	4	236	229	-3	18365	17723	-3
Total	289	22530	20037		1654336	1448840	
Weighted Average				-11			-12

Note:
1 Days that experience recurring congestion.
2 Study methodology.
3 CALTRANS methodology.
4 % difference of the recurring congestion duration estimates of the study and CALTRANS methodologies.
5 % difference of the recurring congestion volume estimates of the study and CALTRANS methodologies.

congestion. In summary, the CALTRANS methodology is expected to underestimate the reduction of congestion due to the implementation of a traffic management system relative to the study methodology.

6.6 Summary

Weekday and seasonal variations of the recurring congestion measure were studied. The stability of this measure over data collection frequency was analyzed in order to establish a sampling plan. One month of data was used to validate the measure. Comparison of recurring and nonrecurring congestion values was conducted. The recurring congestion estimates from the study and CALTRANS methodologies were compared.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This research developed freeway recurring congestion measures applicable to a specific location, a freeway segment, or the entire freeway. These measures were developed to assist in the evaluation of ATMS implementation. A methodology was developed to identify recurring congestion using data reduction and statistical analysis from the freeway system in the Detroit, Michigan metropolitan area. By using the developed methodology and measure, recurring congestion was quantified on the freeway system. Models to identify the start time and duration of recurring congestion were developed, and weekday and seasonal variations of recurring congestion were studied.

The AM and PM peak periods used in the analysis were 6:00-10:00 a.m. and 3:00-7:00 p.m. The results indicated that less than two percent (2%) of recurring congestion occurred outside these identified periods in the eight months analyzed.

The impact of speed thresholds of 30, 35, and 40 mph on the value of the recurring congestion measure was studied. The investigation showed that this measure is not statistically different for any of these three thresholds. If freeway traffic speed falls below 40 mph it nearly always falls below 30 mph. In other words, to measure recurring congestion it is sufficient to use any one of these speed thresholds.

The probability of freeway recurring congestion during the AM and PM peak periods was studied. The study found that the probability of recurring congestion on the freeway system locations ranged between 0 and 96 percent. It was also found that the probability of recurring congestion during the AM peak period increases then decreases as traffic approaches the city center. The same pattern applies during the PM peak period as traffic departs the city center. The probability of congestion occurring during the AM peak period is higher than that of the PM peak period.

The start time and duration of recurring congestion during the AM and PM peak period were studied. The study concluded that the AM peak period congestion starts at a later time and lasts for a shorter duration as traffic flow moves towards the city center. The same pattern applies to the PM peak period congestion as traffic flow moves away from the city center.

The freeway recurring congestion indices and measures values were calculated. It was found that the Probabilistic Location Recurring Congestion and Severity Indices (PLRCI and PLRCSI) of the freeway locations ranged between 0 and 4,144 x 10^{-4} (dimensionless) and 0 and 1,250 x 10^{-2} (mph), respectively. The Probabilistic Freeway Recurring Congestion and Severity Indices (PFRCI and PFRCSI) of the freeway segments ranged between 0 and 1,240 x 10^{-4} (dimensionless) and 0 and 347 x 10^{-2} (mph), respectively. Finally, the Freeway System Recurring Congestion Measure (FSRCM) of the whole freeway system was calculated as 5, 728 vehicle-hours.

A data sampling plan for obtaining quantitative measure of recurring congestion was established. It was found that grouping locations based on the statistical similarity of recurring congestion start time and duration would result in an accurate measure of congestion even if the current detector spacing was increased.

Weekday and seasonal variations of recurring congestion during the AM and PM peak periods were studied, and it was determined that the freeway segment congestion measure is not statistically different during the AM peak period on Mondays and Tuesdays or Wednesdays and Thursdays. The data from Fridays were not significantly different than other weekdays except for one of the freeway segments. The measure is not statistically different during the PM peak period on all weekdays. The freeway segment measure is statistically different in the Spring/Summer than in the Fall/Winter. To measure recurring congestion, data sampling is needed during the AM peak periods on Mondays or Tuesdays, Wednesdays or Thursdays, and Fridays in both seasons. While data during the PM peak period may be obtained on any weekday but it must be collected in both seasons.

The stability of the recurring congestion measure as a function of data collection frequency was analyzed. This analysis was done to determine the minimum number of congested days required for the measure to stabilize (as part of data sampling plan). It was found that 10-12 and 16-17 congested days were required to measure congestion during the AM peak periods in the Spring/Summer and Fall/Winter seasons, respectively. It was also found that 6 and 15 congested days were required to measure congestion during the PM peak periods in the Spring/Summer and Fall/Winter, respectively.

One month of data during the Spring/Summer season was used to validate the developed start time and duration of recurring congestion models. The results showed good agreement between the 8-month and Spring/Summer, and the validation data. The start and end time of the recurring congestion during the validation month lies within both models with a better fit with the Spring/Summer model.

The comparison between recurring and nonrecurring congestion estimated that about 89 and 11 percent of congestion duration in the selected time periods is attributed to recurring and non-recurring congestion, respectively. The study also estimated that about 86 percent of traffic that experienced congestion resulted from recurring congestion. Recurring congestion estimates were significantly higher than other estimates of 33-50%.

The study's recurring congestion duration and volume estimates were compared with estimates using the CALTRANS methodology. It was found that the CALTRANS methodology underestimates recurring congestion duration and volume during the peak periods, in comparison to the study's estimates, by about 11 to 12 percent. This can be explained by the fact that the study methodology is capturing small variations or spikes in traffic speed better than the CALTRANS methodology.

7.2 Recommendations

This research has developed a freeway congestion measure that can be used in evaluating ATMS implementation. The study methodology is expected to account for the reduction of congestion due to the implementation of a traffic management system better than existing methodologies.

Additional data are required to validate the start time and duration of recurring congestion. It is recommended that these data be collected in both Spring/Summer and Fall/winter, based on the sampling plan developed in this research.

In order to determine the minimum spacing of freeway data collection locations required to measure congestion, it is recommended that additional data be collected at locations where detectors were totally not reporting data or number of congested days was less than five days during the 8-month study period. A minimum of five congested days was required to conduct this analysis.

It is also recommended that 6 and 15 additional congested days (based on the sampling plan) be collected during the PM peak periods in the Spring/Summer and Fall/Winter, respectively, to further analyze the stability of congestion during these periods. The analysis is recommended because the study did not show a conclusive pattern during the PM peak periods.

As the study database did not include traffic characteristics on the lane-by-lane level, it is recommended that future studies collect such data on locations where congestion was abnormal.

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