Development of Freeway
Incident-Based Congestion Measures

By

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ABSTRACT

DEVELOPMENT OF FREEWAY INCIDENT-BASED CONGESTION MEASURES

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This research project presents the development of incident-based congestion measures to be used in testing the effectiveness of an ITS deployment program in reducing off-peak incident-based congestion. These measures are used to identify the location and quantify the duration of incident-based congestion on the freeway system as it exists today. These measures are also used to estimate aggregate delay and the characteristics of queues caused by incidents on various segments of the freeway network. To meet these objectives, three measures were established. The first measure quantifies individual station incident-based congestion. The second is a measure of the aggregate impact of individual incidents across freeway segments. And finally, the third measure is an index to quantify system-wide incident-based congestion.

These measures were tested on traffic data obtained from the metropolitan Detroit freeway system. The estimated system-wide off-peak incident-based congestion produces an average of 2.5 minutes of incident-based congestion per station per day. The congestion ranged from a low of 0.4 to a high of 10.5 minutes of delay per day over the 12 segments included in the study.

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TABLE OF CONTENTS

List of Tables

List of Figures

Chapter 1

Introduction

1.0 Description of the Congestion Problem

The growth in urban traffic congestion has become a serious problem in all large metropolitan areas and a cause of discomfort for millions of motorists. Traffic congestion costs the American people an estimated $100 billion each year in the form of lost productivity (1). Congestion has been estimated to be increasing at a rate that will result in 7.3 billion gallons of wasted fuel, and over $50 billion in user cost per year by the year 2005. By then, freeway delay has been projected to have increased by between 300 and 500 percent over the 1985 levels (2, 3, 4).

Although traffic congestion is not a new problem for motorists of the inner cities, it has spread to include the suburban areas. Several factors contributed to the rapid growth of traffic congestion in the United States. First, the number of registered vehicles has increased in a disproportionate rate to the population growth. Second, since the near completion of the Interstate system in the early 1970's, construction of new highway facilities has slowed considerably. Third, because of increased access to the automobile and the suburban migration of both businesses and residents, a higher percentage of commuters now drive instead of using public transit. This change in commuting patterns in addition to the preceding factors has increased congestion on the nation's local streets and highway systems (5). Traffic congestion forces traffic to reduce speed and sometimes causes traffic idling, where tons of pollutants are emitted into the air causing a major environmental problem.

To improve the quality of the nation's traffic facilities and have an efficient and environmentally sound transportation system, Congress passed the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) [6]. Included in this bill was funding for Intelligent Transportation Systems (ITS) with the potential to transport individuals and goods safely and in a more efficient state-of-the-art transportation system.

To alleviate traffic congestion on the metropolitan Detroit freeways, the Michigan Department of Transportation (MDOT) and the US Department of Transportation in conjunction with private firms has planned, developed, and implemented projects using technologies commonly referred to as Intelligent Transportation Systems. Among those projects was the ATMS/ATIS (Advanced Traffic Management Systems/Advanced Traveler Information Systems) deployment program.

Michigan State University has carried out a comprehensive evaluation study to investigate the effectiveness of this ITS deployment program. The study involved an assessment of congestion prior to the ITS deployment, an analysis of the effectiveness of changeable message signs and highway advisory radio; and a study of changes in the frequency, duration, and location of incident-based congestion. This study addresses the effectiveness of the system in reducing incident-based congestion.

1.1 Project Location and Description

The system deployed augmented an existing freeway monitoring and control system covering 32.5 miles of the urban freeway network. The combined system covers a total of 180 miles. CCTV cameras, machine vision and induction loop detectors, changeable message signs (CMS), ramp meters, and highway advisory radio (HAR) were installed as components of the ITS deployment program. Rockwell International designed and built the system that covered selected freeway segments of I-75, I-94, I-96, I-275, I-696, M-10, and M-39. Figure 1.1 illustrates the system that existed prior to the expansion (known as SCANDI) and the newly instrumented system. The type and location of the various components of the ITS deployment program are shown in this figure. The program became fully operational in September 1998.

1.2 Benefits of the ITS Deployment

The benefits MDOT anticipated from the ITS deployment program included:

- Providing the Michigan Intelligent Transportation Systems (MITS) Center in Detroit the capability to monitor traffic and congestion through the use of mainline traffic detectors (loops and machine vision), ramp metering and video surveillance;
- Providing traveler information via highway advisory radios (HAR) and changeable message signs (CMS);
- Providing the Michigan DOT the means to detect and verify incidents on selected corridors in a timely manner;
- Providing traffic operations personnel sufficient data to respond to incidents and to transmit traffic and congestion information to motorists so they can select or modify their travel plans;
- Providing the data required to effectively manage mainline work zones, calculate mainline volume demand, and predict traffic flow patterns for special events, planned work/constructions zones, and other special conditions.
- Improving the safety of the area's transportation system;

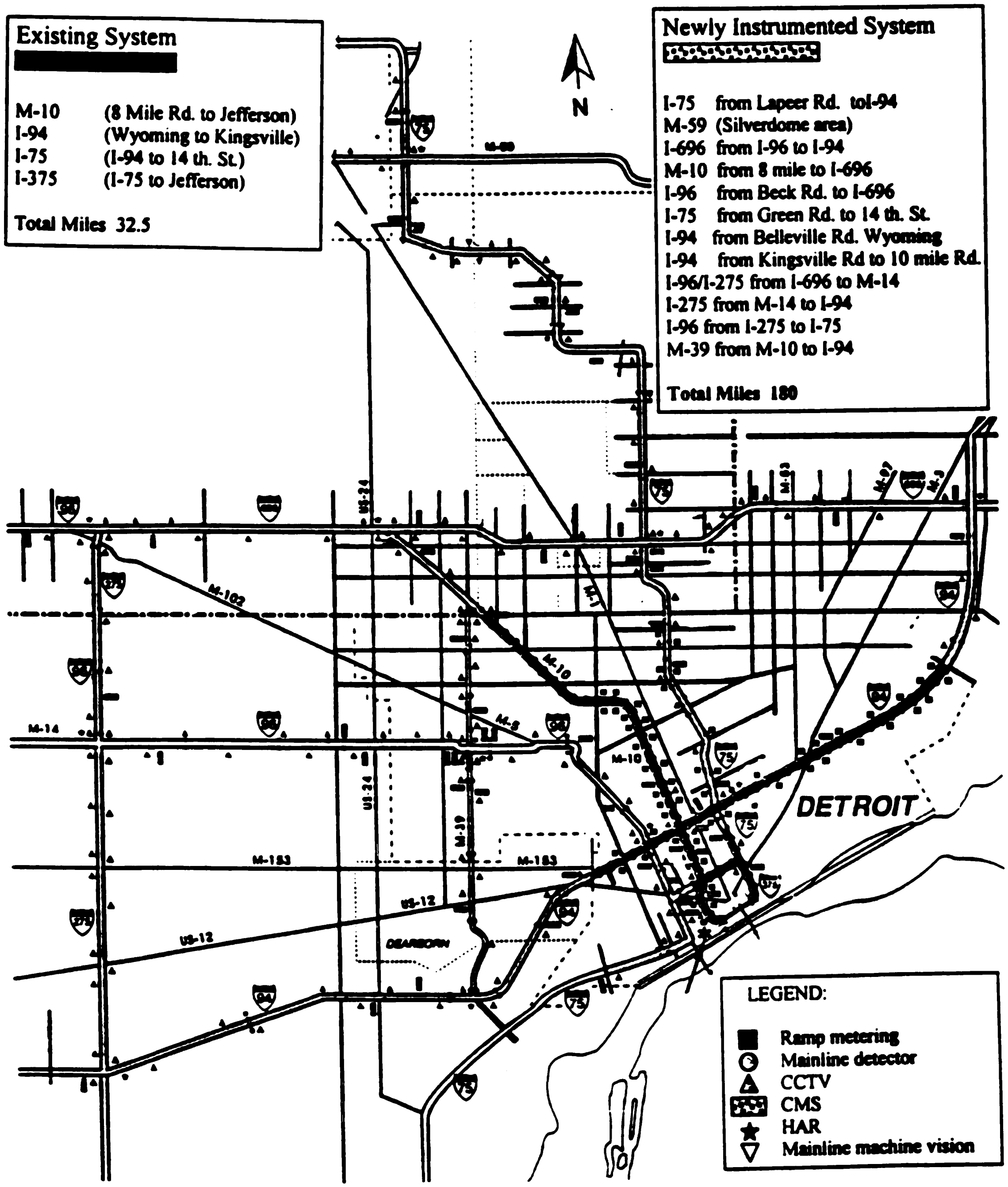


Figure 1.1 South eastern Michigan ITS-ATMS/ATIS deployment program

- Reducing energy and environmental costs associated with traffic congestion; and finally,
- Enhancing present and future productivity.

1.3 Statement of the Problem

Over the past 10 years, research, development, and implementation of ITS technologies has expanded in fields such as information processing, communications, control, and electronics to serve transportation needs. ITS technologies can provide many benefits, one of which is to improve the ability to manage recurring and non-recurring congestion through more efficient use of the existing or improved infrastructure. ATMS/ ATIS is expected to reduce traffic demand following an incident by providing motorists with information on delay due to congestion and alternate routes, which will increase the rate of diverted traffic and reduce the gap between demand and reduced capacity.

1.4 Objectives and Scope of the Research

There were three objectives for this research project. The first involved identifying and quantifying the frequency, duration, and location of incident-based congestion. The next objective was to estimate delay and the characteristics of queues caused by incidents on various segments of the freeway network. The third objective was to evaluate the net reduction in the impact of incidents attributed to the expansion project. To meet these objectives, the following tasks were identified and addressed:

- Developing a technique to measure the changes in congestion;
- Collecting historical data on the SCANDI system before the ITS deployment;

- Analyzing data to determine the frequency, duration, and location of incident-based congestion prior to the ITS deployment;
- Developing an index to quantify the level of incident-based congestion.

1.5 Research Methodology

This research project focused on the congestion caused by incidents during off peak periods. The morning and evening rush hours were considered to be from 6:30 AM to 9:30 AM and from 3:30 PM to 6:30 PM, respectively. Congestion that occurred during this time was included in another study. This study utilized traffic volume and speed data obtained from the Michigan Intelligent Transportation Systems (MITS) Center. The data included minute by minute average values of volume, occupancy, and speed as well as an indication of the number of lanes and the number of lanes reporting data at various locations on the freeway network. Data was gathered on the detector stations within the SCANDI system for one month of 1996 and eight months of 1997.

A speed threshold value was set to define congestion, and incidents were flagged based on this value. To determine the duration of an incident, a criterion was developed to determine an incident's start and end times. Next, the queue length parameters of incidents that covered more than one station were estimated. The incidents were then divided in different groups based on their queue length, and their total impact was summed for various segments of the network for each month. The network freeways were divided into segments of various lengths to help identify areas with high incident rates, as well as to reduce the effect of malfunctioning detectors on the outcome of this research. This division will also allow easier before and after comparisons to determine whether the ITS deployment had different effects on incident frequency and duration on the different segments of the network.

Chapter 2

Literature Review

2.0 Introduction

A literature review was conducted to obtain the current state-of-the–art related to the research study described in chapter 1. The literature search was performed to accomplish three primary goals. First, the current knowledge related to traffic congestion and traffic incidents was explored. Second, literature was used to develop an understanding of how similar problems were approached in the past, and to help develop new ideas to resolve the problem under investigation. Third, three ATMS/ATIS evaluation studies were reviewed to determine the potential role of ITS in managing incident-based congestion.

The following sections of the literature review have been divided into the main areas of traffic research related to this study. They include research conducted on traffic congestion and it's related topics followed by traffic incident characteristics and measures of incident duration and delay. The third topic presents similar evaluation studies cited in the literature. The fourth part describes the role of ITS in reducing incident-based congestion. Finally, a summary of the literature review is included.

2.1 The Congestion Problem

Because of the close relationship between traffic congestion and traffic incidents, the literature that is related to traffic congestion was included in the literature review.

The relevant topics; measures of congestion, types of congestion, and measures to alleviate congestion are presented in the following subsections.

2.1.1 Measures of Congestion

Congestion is defined as a "*condition of overcrowding on a roadway caused by demand exceeding capacity which is manifested by high densities, low volumes, low speeds, stop-and go driving, increased delay and a high rate of rear-end collisions occurring upstream of the bottleneck*" [7]. Congestion is described as a phenomenon that is measured by using different variables in equation formulas to describe the extent, severity, and duration of congestion. One type of measuring congestion uses indicators that are related to the level of congestion as well as the probable cause of congestion. Examples of possible indicators include vehicle miles of travel per lane mile of roadway, and population density. Another type of measure uses variables that are descriptors of the effects of congestion. Vehicle delay, congestion duration, and average travel speed are all examples of variables that describe the effects of congestion [5]. The following paragraphs present the two types of measuring congestion.

The Highway Capacity Manual (HCM) [8] adopted the Level-Of-Service (LOS) concept to represent a range of operating conditions. The LOS of a facility is determined by traffic variables such as vehicle density and volume to capacity ratio (v/c), depending on the facility type. The HCM describes traffic behavior at Level Of Service D as unstable with limited space to allow for minor disruptions. The average travel speeds at this level are greater than (46, 42, 40) mph for the design speeds of (70, 60, 50) mph respectively. Capacity is reached at the border of LOS D and E with an average travel speed of 30 mph. At LOS E, traffic operates under an extremely unstable condition where all space is utilized and a slight disturbance is sufficient to cause a breakdown in flow with deterioration to LOS F. Congested traffic conditions fall into the LOS F range that is used to define forced or breakdown flow. In this range, traffic demand exceeds the capacity of the roadway.

The General Accounting Office (GAO) [9] study found that on Urban Interstate Systems, the total travel delay is relatively insensitive to changes in v/c between 0.77 and 0.99. This range covers LOS C, D, and E for the design speeds of (70, 60, 50) mph. The study also included the definition of congestion used by several metropolitan planning organizations, local governments, and the California Department of Transportation. The study considered the road as congested once v/c and the average travel speed were near 1.00 and 35-mph respectively.

CALTRANS attempted to better describe the duration of congestion by using the number of hours of LOS F [10]. For example, LOS F2 represents 2 hours of LOS F. They believed that the combination of the v/c ratio and the duration of congested operation enhance the LOS concept alone and account for the peak spreading that is common in many urban areas. They found this improved measure relatively easy to calculate, interpret, and communicate.

An analysis technique developed by Lindely [3,4] to measure congestion used Highway Performance Monitoring System (HPMS) data, traffic distribution patterns, and the Highway Capacity Manual to calculate freeway travel delay. He defined the congestion severity index as the total freeway delay in vehicle hours per million vehicle miles of travel. Then he ranked urban freeway systems according to the congestion severity index. He also developed a methodology to calculate delay caused by incidents using an accident database of breakdown types and rates. In Lindley's calculations, the congestion threshold was defined at a v/c ratio of 0.77 or higher (LOS D or worse) during 1 or more hours per day.

Lomax and Christiansen [11] investigated the use of several variables as indicators of areawide congestion levels. Among those presented as possible indicators were traffic volume per lane, percentage of freeway lane miles of ADT greater than 15,000, K-factor, and peak hour travel distance per lane mile. They calculated these possible indicators for 1975 to 1980 for five urban areas in Texas. Their study concluded that VMT per lane was perhaps the most reliable indicator and developed a congestion standard that combined weighted values for freeway and principal arterial street VMT per lane mile. Subsequent research by Lomax et al. resulted in the development of a roadway congestion index (RCI) [5, 12]. The indicator of daily VMT (DVMT) per lane mile for both freeways and principal arterial streets was weighted and normalized in the index's equation. They ranked major U.S. urban areas according to the RCI value. Their chosen threshold value for congestion was at a v/c ratio of 0.77 or higher and correlated to ADT per lane mile values for freeways and principal arterial streets through basic assumptions about traffic characteristics.

Thurgood [13] defined congestion based on the LOS dropping from E to F as determined by speed measurements. He used speed as a traffic parameter for the reason that it is easy and relatively low in cost to measure, and because most agencies prefer to use speed to measure congestion.

Gall and Hall [14] proposed logic to distinguish between incident and recurrent congestion. The logic consisted of two major steps. The first step classified traffic operations on a freeway facility into four states on the bases of volume and occupancy graphs. States 1 and 2 were separated from states 3 and 4 by an occupancy of 25 percent. A minimum discharged volume of 1,920 vehicles per hour per lane was used to separate states 3 and 4. States 1 and 2 were separated by a non-linear line constructed by using detector data that was considered to represent uncongested operations based on speed above 40 miles per hour and occupancy less than 25 percent. The second step of the logic used the information obtained from step 1 to determine the cause of congestion.

Cottrell [15] developed a lane-mile duration index ($LMDI_F$) as a measure of recurring freeway congestion in urbanized areas. The $LMDI_F$ represents a summation for an urban area of the congested freeway lane miles multiplied by the respective duration of LOS F. The use of the duration of LOS F service in intermediate calculations of $LMDI_F$ is similar to Caltrans reporting of LOS F2. Cottrell chose LOS F as the congestion threshold, which he correlated to an AADT/C value of 9, where C is the capacity.

2.1.2 Types of Congestion

Congestion can be divided into recurring and non-recurring congestion, and congestion due to special events. Recurring congestion is repetitive in nature and occurs regularly during peak periods when traffic demand exceeds capacity. Peak period congestion occurs daily and is expected to occur with some predictability and regularity in both effect and duration [16]. Distinguishing between recurring and non-recurring congestion might be achieved by examining the type of bottleneck or by calculating travel time [17]. Recurring congestion is most often associated with a permanent geometric bottleneck, such as a heavily used entrance ramp, a horizontal curve in the roadway, a steep grade or the termination of a lane [7]. In addition, travel time builds up slowly in this type of congestion. Recurrent congestion has received considerable attention during the past 30 years, leading to the development of freeway ramp control strategies that have shown their effectiveness in reducing recurrent peak hour congestion [18].

Non-recurring congestion is unpredictable and is usually associated with unscheduled and essentially random events such as incidents that may cause a reduction in the freeway capacity below the level of demand. Environmental changes such as heavy rain, ice, snow, fog, etc., might also fall into this category. Not all incidents result in significant delay, however lane blocking incidents during the high traffic demand create queuing on the freeway, which can be a serious traffic hazard to uninformed motorists and may lead to secondary accidents. Adverse weather conditions may reduce capacity in the case of major storms including times when partial or total freeway closures might be necessary. Travel time in this type of congestion changes suddenly [16].

Special events such as ballgames and parades often generate large volumes of traffic that is relatively predictable in magnitude and space. Traffic planners can predict the effects of many special events from their historical data and manage congestion by diverting traffic to alternate parallel routes. Operational studies have shown that managing traffic during special events could result in a substantial reduction in congestion and delay [19, 20].

2.1.3 Measures to Alleviate Traffic Congestion

The historical solution to satisfy the growing traffic demand was through new freeway construction and/or freeway-widening programs. However, as these new freeways were built or lanes were added, the added capacity was filled almost as soon as the freeways were opened to traffic. Therefore, less expensive alternatives were sought, among which the Intelligent Transportation Systems (ITS) was chosen as a promising technique to reduce congestion.

When a capacity-reducing incident occurs on the freeway, the optimal control strategy is to immediately intercept freeway traffic before it reaches the reduced capacity, and to prevent additional vehicles from entering the freeway at upstream entrance ramps. Vehicles involved in the incident must be removed as quickly as possible and the demand must be redirected to areas of available capacity in the freeway corridor. Additionally, to reduce secondary accidents, drivers approaching the queue area should be warned of the slow traffic [(16)].

Surveys [(21, 22, 23,18)] showed that a significant number of motorists would take an alternate route around congestion if they had prior knowledge of the location and magnitude of the congestion. They often cite the need for more accurate information as being their primary factor on deciding whether to divert or not. For motorists to react to the information, they must believe that the information accurately reflects the current travel conditions [(24)]. Therefore, operators of freeway management systems must have information that is both accurate and current.

2.2 Characteristics of Traffic Incidents

To effectively manage traffic incidents and reduce their impact on freeway operations, many researchers felt the need to quantify the characteristics of the traffic incidents and determine the factors influencing their occurrence. Incident characteristics can be described in terms of incident rates, incident duration, and incident severity. These characteristics are presented in the following subsections.

2.2.1 Incident Definition

Many authors have defined incidents. Judycki [25] defined an incident as "*a random event such as an accident, stalled vehicle, or a spilled load that causes a reduction in the capacity of the roadway* ". Guiliano [26] described an incident as "*any occurrence that affects roadway capacity, either by obstructing travel lanes or by causing gawkers block*". Another definition was stated by Urbanek and Rogers [27] as "*a spill, breakdown, accident, or any other extraordinary event that causes congestion and delay by restricting normal traffic flow*". These definitions suggest that random events that may disturb the normal flow of freeway traffic may be considered as incidents causing a temporary bottleneck where one would not normally occur.

2.2.2 Incident Types

Incidents have been categorized by type as accidents and other incidents [26]. The reported relative frequencies of incident types are quite diverse. Accidents were cited as high as 49% [28] and as low as 6% [29] of the total observed incidents. A higher percentage of accidents result in lane blocking incidents due to the fact that vehicle disablements often allow the driver to leave the traveled way immediately, or to reach the shoulder before the vehicle is completely disabled [28].

2.2.3 Cost of Incidents

In 1993, traffic accidents claimed 40,115 lives and injured an additional three million people in the United States [1]. In a metropolitan freeway network, at least one lane is expected to be blocked per mile of freeway 7.2 percent of the time because of accidents, 6.7 percent of the time as a result of stopped vehicles, and 27.8 percent of the time due to maintenance activities [30]. Arceneaux and Mikhalkin have determined that almost 60% of the vehicle-hours lost on an urban roadway system is a result of non-recurring congestion [31]. Freeway incidents in urban areas are recognized as a disruption problem that accounts for more than 50 percent of all freeway congestion [32].

On urban freeways, non-recurrent congestion caused by incidents was noted to be responsible for as much motorist delay as the recurring congestion caused by a geometric bottleneck [33]. A study conducted by the California Department of Transportation (CALTRANS) has estimated that more than 50 percent of all delay to motorists on the freeway systems are the direct result of an incident [34].

In Texas, freeway incidents in 1990 were the cause of over 440,000 vehicle hours of delay, costing the motorists approximately $2.2 billion. In Houston, over $1.5 billion are lost annually due to congestion and over 59% of this cost is due to delays and excess fuel consumption resulting from incidents. On a per capita basis, the cost of congestion in terms of delay and fuel consumption is estimated to be approximately $440 per person annually, and total congestion cost per registered vehicle is $695 annually when the cost of insurance is considered [34].

Another study (Robinson, J., 1990) estimated that the impacts of incidents in terms of hours of delay, wasted fuel consumption, and excess road user costs have increased 5 fold over levels experienced 10 years prior to the study [35]. Goolsby found that a stalled vehicle caused a delay of 1,610 and 2,940 vehicle-hours for a one lane and two lane closure, respectively [36].

2.2.4 Incident Rates

Incident rates are location dependent. Differences are due to factors such as road geometry, level of traffic demand, weather, grade, and shoulder availability [37]. Incident rates are generally expressed as incidents per hour per lane-mile [28,36,38], incidents per million vehicle-kilometers (MVK) [38, 39, 40], or daily rate per freeway segment [26]. Table 2.1 shows incident rates from five different locations in the United States. The first three rows shown in the table were lane-blocking incidents of all types observed via closed circuit television. The substantially higher rate of the third row is most likely due to the absence of shoulders on the Bay Bridge.

Guiliano [26] conducted a study to describe incident patterns and analyzed incident duration as a function of incident characteristics on a 12-mile section of the I-10 freeway located in Los Angeles, California. The I-10 freeway has 5 lanes in each direction over most of its length. Accidents were found to be most frequent on weekdays. The daily average weekday rate was 3.1 accidents per million vehicle miles and the weekend daily rate was 2.2. Friday had the highest daily rate of 3.8, while the lowest daily rate of 2.0 occurred on Sunday.

An estimate of incident rates in Houston was 0.68 incidents per 100 million vehicle-kilometers (MVK). This is equivalent to a major incident every 147 MVK [42].

Table 2.1 Incident rates.

Unit of Measure	Location	Rate
Lane-blocking incidents per hour per lane-mile [28]	Detroit, Michigan	0.014
Lane-blocking incidents per hour per lane-mile [36]	Gulf Freeway, Houston, Texas	0.010
Lane-blocking incidents per hour per lane-mile [38]	Oakland Bay Bridge, California	0.036
Incidents per million-vehicle-miles [40]	Toronto, Canada	19
Incidents per million-vehicle-kilometers [41]	San Francisco, California	65
Fatal accident rate per 100 MVKm [42]	Houston Freeways, Texas	0.708

Frank DeRose Jr. [28] performed a study to determine the frequency, duration and character of the freeway traffic incidents in addition to the proportion of accidents to incidents in Detroit. He indicated that accidents were about twenty five percent of the total number of incidents. The number of incidents increased during the periods of high traffic demand when the capacity was exceeded. He calculated the rate of incidents per mile as well as total incidents per million vehicle-miles for the total 3.2 mile study section. He found that the rates per million vehicle-miles were 11.9 and 8.7 incidents for the 4 and 3 lane sections respectively, and the average daily incidents per mile rate was 0.69 and 0.51 incidents for the 4 and 3 lane sections respectively. Climatic conditions showed higher frequencies at low temperatures, rain, snow, and wet pavement. The average duration of 927 incidents was 6.14 minutes for accidents, 4.94 minutes for vehicle disablement and an over all average of 5.24 minutes. The average duration of the incident was defined as the time the incident occurred to when the incident was removed to the shoulder or when the freeway resumed movement.

2.2.5 Behavior of Traffic in the Presence of an Incident

When an accident occurs on a high-volume freeway, most likely a queue will form at the location of the incident. The queue and its resulting congestion then begin backing upstream from the site of the bottleneck. Whitson [(43)] has presented volume-density plots of freeway operations in Houston during an incident, which clearly illustrate this upstream progression of the queuing area. The frontal boundary of this queue as it moves upstream is called a shock wave and commonly travels at speeds of 10-20 mph during moderate to heavy traffic conditions. Whitson also noticed that there was a second wave moving downstream from the incident location. This wave explains the change that occurs downstream of the incident, from normal flow to a much lighter flow.

Figure 2.1 is a graphical illustration of freeway traffic behavior upstream and downstream of an incident location when the incident partially or totally blocks the freeway. Upstream from the incident, the characteristics represent traffic conditions moving at normal speeds and normal density k_n. The area located immediately upstream of the incident represents the congested area where vehicles are queuing and traveling at low speeds and experiencing high density k_q. The region immediately downstream of the incident reflects traffic flowing at a metered rate with low density and slightly higher speeds than the normal flow. The far downstream area from the incident represents traffic flow similar to the area far upstream of the incident with normal traffic flow and normal density k_n [44]. This behavior continues until the incident is completely removed and the queued vehicles upstream of the incident are completely discharged. W_{u1} and W_{d1} represent the speed of the upstream and downstream shock waves respectively.

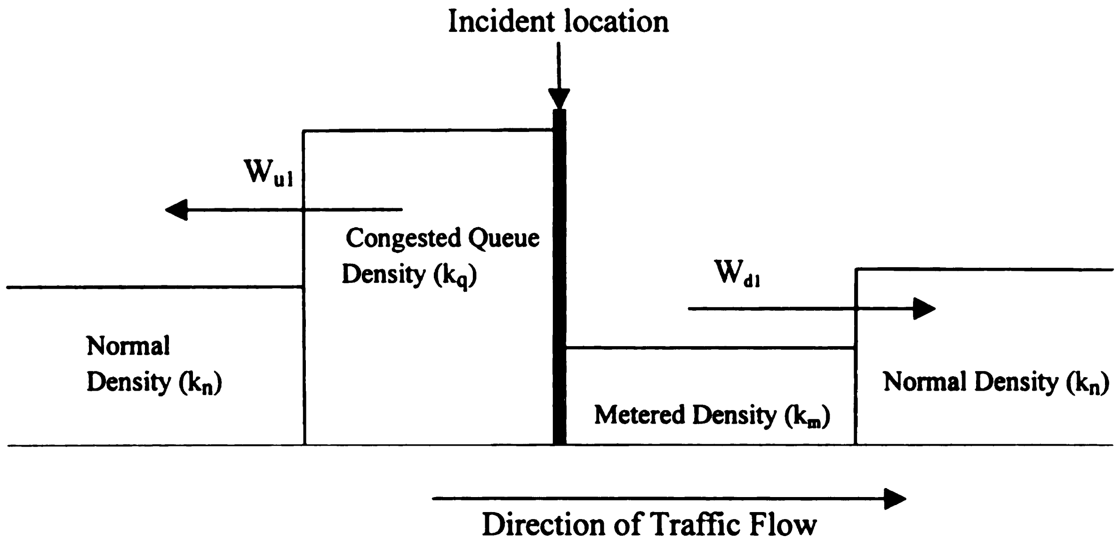


Figure 2.1. Behavior of traffic under an incident.

2.2.6 Impact of Incidents on Capacity

Merrel E. Goolsby [36] found that incidents created a reduction in flow disproportionate to the physical reduction in roadway width. He noticed that an incident removed to the shoulder on a three-lane freeway reduced capacity by one third due to the gawkers block phenomenon, even though no physical obstruction exists; a single lane blockage reduced capacity by 50 percent, even though the physical reduction is only 33 percent; and a two-lane blockage reduced capacity by 79 percent. Lindley [3] determined the reduction in capacity due to an incident as a function of total lanes and the number of blocked lanes. He found that the amount of capacity reduction is greater than the percentage of blocked lanes to the total number of lanes. He also found that shoulder disablement seems to have little or no effect when the total number of lanes is more than two.

McShane et al. [45] presented an example to illustrate the effect of capacity reduction on the volume to capacity ratio. They considered three different values for v/c ratios and then they simulated the losses in capacity due to an incident by changing these three values by different percentages. They illustrated that decreasing capacity by 10% can change freeway operation from a functional system to an oversaturated system depending on the demand level at the capacity reduction time.

2.2.7 Incident Duration and Delay

Traffic demand has a significant impact on incident duration and its associated delay. As long as demand is below the reduced capacity, all vehicles passing the incident will experience no delay. On the other hand, once demand exceeds capacity a queue will build upstream of the incident causing excessive delay to motorists. The rate at which the queue builds depends on the difference between demand and the reduced capacity. The research dealing with incident duration is presented first followed by a discussion of incident delay.

The highway capacity manual [46] divides incident duration into four intervals. The first interval represents the time between the occurrence and verification of an incident. The second interval represents the time between the incident verification and the arrival of the police or towing vehicles to clear the incident. The third phase represents the time between the arrival of these vehicles and the clearance of the incident. The last phase represents the recovery time or the time required for traffic conditions to resume normal operation. Effective incident management can reduce incident duration by minimizing the detection, response, and clearing time of an incident and reduce the recovery time. The primary factor influencing incident duration is the traffic demand that can be controlled by diverting and restricting demand upstream of the incident site by using ramp metering, changeable message signs or any other diverting technique.

The impact of incidents on freeway operations was investigated by Merrel E. Goolsby [36] by relating frequency, duration, and flow passing freeway incidents in order to estimate the magnitude of motorists delay resulting from incidents on the Gulf Freeway in Houston. In two years, 1,154 accidents were studied. They found that the average accident required 19 minutes from the time of reporting to removal from traffic lanes and an additional 26 minutes for the police investigation.

Guiliano [26] used three different data sets to develop a statistical model to estimate incident duration based on incident characteristics. She developed two separate models, one for all incidents and the other for accidents. In these two models, she used qualitative categories representing incident type, lanes closed, time of day, accident type, and truck involvement as independent variables. One of her most important findings was the highly significant effect of truck involvement in accident duration, where the presence of a truck in an accident causes a substantial increase in total duration.

Several methods have been developed to estimate incident delays. These methods can be classified into three types. The first method is based on queuing analysis [46, 47]. The second method is based on shock wave analysis [48, 49, 50]. The third method is based on freeway traffic simulation [51,52]. The research cited regarding these methods is presented in the following paragraphs.

The Federal Highway Administration (FHWA) funded research in the late 1970's to develop guidelines and recommendations to help highway departments, police agencies, and other organizations select, plan, design, and implement low-cost-measures to deal with incidents that cause freeway congestion. The research was published in reports presenting an overview of the nature and magnitude of the freeway incident management problem and summarized possible solutions [53]. The reports also included analytical procedures to estimate traffic delay and congestion and assess the tradeoffs in cost-effectiveness among many alternative measures.

Morales [47] summarized the basic analytical procedures presented in these reports and developed a model for computing delay, time to normal flow (TNF), and maximum queue (Q_{max}) caused by freeway incidents. He quantified delay based on a graphical representation of cumulative arrival and departure curves and calculated the cumulative vehicle hours of incident delay. He divided the congested time period into smaller time intervals during which demand and/or capacity is assumed to be constant, resulting in linear arrival and departure curves at the incident bottleneck. The method assumed that the initial demand was less than the capacity of the roadway section. The queue length was calculated as the algebraic difference between the cumulative demand and the cumulative departures at any time (t).

The highway capacity manual method uses the same approach as Morales [47] method with an important modification that considers cases of incidents occurring during the peak period of congestion with initial demand exceeding capacity. The two methods are widely used by practitioners and researchers to estimate incident delay.

Garib et el. [54] presented two regression models for estimating freeway incident congestion and a third model for predicting incident duration. They used two sets of data from Interstate 880 in Alameda County, California. The first set of data was collected using a fleet of moving observers during morning and evening rush hours reporting on observed incidents and their characteristics. The other set of data was obtained from freeway loop detectors. They used multiple regression analysis to develop incident delay models using these two sets of data. The first delay model calculates delay as a function of incident duration, traffic demand, and capacity reduction. These are the exact variable used by Morales [47]. Their second model predicts the cumulative incident delay as a function of incident duration, number of lanes affected, and number of vehicles involved. The last model was a statistical model to predict incident duration as a function of number of lanes affected, number of vehicles involved, truck involvement, time of day, , police response time, and weather condition.

Messer et al. [48] used the kinematics wave theory of Lighthill and Whitham to develop a method for predicting individual travel times on the freeway during incident conditions. They divided the time space plane during incidents into areas representing four different traffic flow conditions: normal flow, queue flow, metered flow, and capacity flow. The boundaries of these areas were defined by linear shock waves, and the speed of each shock wave was derived assuming a linear speed-density relationship developed by Greenshields [55]. They applied the method to four incidents that occurred on the Gulf Freeway in Houston. They found that two-thirds of the observed travel times were within 10 percent of the predicted travel times. The linear Greenshield's speed-density model results in parabolic curves for volume-speed and volume-density plots. The major problem with using the parabolic curves is that if they do not match the actual conditions in regions upstream of the incident then significant errors result in calculating the wave speeds.

Wirashighe [49] applied the shock wave theory of Lighthill and Whitham to develop formulas independent of any particular macroscopic theory of traffic flow for calculating individual and total delay upstream of incidents. The formulas are based on areas and densities of regions representing different traffic conditions that are mainly congested and capacity regions that are formed by shock waves in the time-space plot.

We-Min Chow [50] performed a study of traffic performance in the presence of an incident using shock wave and queuing analysis under the assumption that traffic density is not a function of time and a unique flow-density relationship exists. He derived formulas to calculate total delay, which he found yielded identical results. His study proposed two methods; the first was to compute the duration of time to discharge stored vehicles after the incident is removed. The second was to calculate delay in terms of the difference between total travel time under the incident and non-incident cases. He concluded that if he had used a time dependent flow-density relationship which is more realistic, then the two methods would have given different results.

Wicks and Lieberman [51] developed INTRAS, a microscopic freeway traffic simulation model designed for freeway corridor simulation. INTRAS was enhanced and the new version called FRESIM has been used in the past few years. Both versions share the same fundamental structure based on car-following theory. Cheu et el. [56] used INTRAS and data from a Los Angeles Freeway and concluded that INTRAS may underestimate the occupancy during free flow conditions in the recovery periods after incidents. In addition, they indicated that the car-following theory equation used in INTRAS gave satisfactory results in general, but failed to produce high volume and occupancy values that match collected field values in their study site. INTRAS and FRESIM can be used to estimate incident congestion by simulating the freeway with and without the incident and calculating the difference in vehicle hours of travel.

2.3 Prior ATMS/ATIS Evaluation Studies

Three FTMS evaluation studies were cited in the literature and are presented briefly to illustrate the significance of FTMS implementation in improving the quality of freeway operations. The first study was conducted in Toronto, Canada to evaluate COMPASS and the second study was performed in New York to evaluate INFORM. The last case was performed in Korea.

2.3.1 COMPASS (Toronto FTMS evaluation study)

The Ontario Ministry of Transportation implemented a Freeway traffic management system (FTMS) called COMPASS in 1980 to improve the quality of traffic on Freeway 401 in the Toronto area. The system included CMS, CCTV, and loop detectors. The primary goal of COMPASS was to reduce congestion by balancing traffic between the expressway and collector lanes. This balancing was intended to manage the demand in an efficient way and ensure that any spare capacity on either roadway becomes available to all traffic as needed. The parallel roadway system allowed vehicles to bypass congestion and incidents by moving to the adjacent roadway. The COMPASS system calculates travel time between two transfer points, and a balancing message is displayed when a significant change is observed. Speed was used as a single parameter to calculate link travel times.

Masters et el. [57] performed a before and after study by using volume as the control parameter to ensure that the before and after data sets were suitable for comparisons. Only a 5% variation was allowed in the study. Incidents with duration less than 5 minutes were ignored. The findings included a reduction in secondary accidents by 70% on the Burlington Skyway as a result of quick detection, response and removal of incidents and a lowered congestion level due to reduced time of lane blockage and diversion resulting from the pre-warning to drivers. Moreover, average speeds on the skyway were increased between 7% and 18.6%, and the travel time was reduced by the same amount.

2.3.2 INFORM (Information for Motorists, New York FTMS evaluation study)

INFORM is a corridor traffic management system designed to improve the utilization of the existing freeway facilities. It contains two major freeway facilities, the Long Island Expressway (LIE) and the Northern State Parkway/Grand Central Parkway (NSP/GCP) in Long Island New York. The system also includes a number of crossing and parallel arterials and freeways forming a total of 128 miles of controlled freeway. Parallel freeways such as the LIE and the NSP/GCP offered an opportunity to divert. The system consists of electronic monitoring, variable message signing, ramp metering, a limited number of CCTV, road side citizens band radios, and arterial streets intersections under INFORM control.

Steven and Perez [18] evaluated INFORM using field data and perception surveys. The measures of effectiveness used to assess INFORM were; vehicle miles of travel; average speeds; ramp delays; motorists perceptions; and effectiveness of changeable message signings.

The system used passive message signs, and their effect was observed during incident conditions by monitoring changes in the volume of upstream off-ramps. The operators used the changes in ramp volumes as an indication of how effective the messages were. For a typical incident and using passive messages 5 to 10 percent of mainline traffic in the INFORM corridor was diverted over several upstream off-ramps. Volume on these ramps was increased by 40 to 70 percent for up to three upstream off-ramps.

Speeds were compared for metered and non-metered periods in both the AM and P.M. Morning peak period freeway speeds for the March 1990 metering increased 3 to 8 percent over speeds for March 1990 non-metering and 13 percent over speeds for spring 1987. For the P.M. traffic speed, no change in speed was observed for the metered and no-metered conditions. Delay savings for the peak period incidents were analyzed and the annual delay savings for the incident related effects of CMS were estimated. Estimated delay savings for the peak period incidents analyzed ranged up to 1,900 vehicle-hours. The estimated annual delay saving for the incident-based effects of the variable message signs was 300,000 vehicle-hours.

Residents were surveyed in the INFORM area to obtain their opinion of the usefulness of the information displayed, and whether they changed their routes in response to the messages. Twenty five percent of the motorists viewed INFORM as a helpful system and 45 percent thought that INFORM helped once in a while. 45 percent of the drivers stated that they sometimes change their route in response to the sign messages and 25 percent never changed their route in response to these messages. They were also asked about their choices once they encountered an on-ramp red signal and the time they spent waiting at red signals. Fifteen percent of those who encountered an on-ramp red signal indicated that they used the service road or other roadway to avoid waiting. Moreover, the survey included the resident's opinions on CMS and ramp metering.

Their over all findings were that the system produced delay savings. There were however, cases of arterial breakdown during heavy diversion. The residents expressed a positive attitude on CMS and mixed feelings over ramp metering.

2.3.3 The Korean FTMS Evaluation Case

Korea initiated a Freeway Traffic Management System (FTMS) in 1992 and it went through an operational test in February 1995. The system covered 318 kilometers of freeway segments of Kyoung-Bu and Chung-Bu express highways that connect Seoul and Daejon.

Kyungsoo et el. [58] presented a paper describing the Korean FTMS evaluation study. They performed quantitative and qualitative analyses to assess the benefits of the system. Their quantitative analysis included the calculation of the reduction in recurring and non-recurring delay and estimated the monetary benefit from delay reduction achieved by the installation of the FTMS. Reduction in recurring and non-recurring delay due to the FTMS installation was estimated to save 65 and 9,320 million US dollars respectively from the time the system became operational through the year 2004. For the qualitative analysis, they conducted a survey to obtain the motorist's opinion and level of satisfaction over the system's performance. Their study showed that 65 percent of the freeway users acknowledged the effectiveness of the system, 95 percent of the motorists were satisfied with the accuracy of the information provided, and 68 percent requested information on alternative routes. The overall outcome of the study showed a reduction in delay as well as an encouraging acceptance from the motorist.

2.4 The Role of ITS in Managing Incident Based Congestion

In recent years, ITS technologies have been incorporated with incident management systems to assist in alleviating non-recurrent congestion in most metropolitan areas in the United States. Incident management is defined as a planned and coordinated procedure developed to eliminate the impact of incidents on traffic operations as quickly as possible. It involves collective efforts of human, mechanical, and electronic resources to serve different purposes. These purposes include detecting and verifying the incident and assessing its magnitude as well as identifying what is needed to restore the facility to normal operation. It also helps to provide the appropriate response in the form of control strategies, and information dissemination [40]. The following subsection reviews incident detection methods, incident response and clearance, and finally, electronic incident management and control strategies.

2.4.1 Incident Detection and Verification

Rapid detection is one of the most important elements in incident management. The sooner an incident is detected, the faster the response to initiate its removal. It has been noted that emerging Intelligent Transportation Systems technologies offer a promise to substantially improve detection capabilities and reliability. Technologies available for detecting incidents range from low-cost non-automated methods to sophisticated automated surveillance techniques.

The effectiveness of automatic detection technologies depends in part on the type of algorithm used to analyze the detector data. Three parameters generally used to monitor the performance of an incident detection algorithm are detection rate, detection time, and false alarm rate (62). Detection rate is defined as the percentage of the total number of incidents that are detected by the computer algorithm. Detection time is defined as the time between when an incident occurred and the time it is detected by the algorithm. The false alarm rate is generally used to provide an indication of how many times the algorithm incorrectly flags an incident.

There is a general relationship that exists between detection rate, false alarm rate, and detection time. With most incident detection algorithms, the false alarm rate increases as the detection rate increases. Also, the false alarm rate increases as the detection time decreases. This is because as the sensitivity of the algorithm is adjusted to detect less severe incidents more quickly, minor fluctuations in traffic can trigger the algorithm to signal that an incident is present, when in fact no incident exists on the freeway. False alarms can be tolerated in order to achieve higher detection sensitivity, as long as they are not too frequent and can be ignored by the system operator. Evaluation of false alarm rates is based on their frequency over a given time period. An algorithm may be reported as having a very small false alarm rate percentage but yield a fairly high number of false alarms because the total number of such checks made during a given time period is so high.

The five general categories of incident detection algorithms that rely on volume, speed, and or occupancy data include the following: [63]

- Comparative.
- Statistical.
- Time-series/smoothing.
- Traffic and theoretical models.
- Advanced incident detection techniques

Comparative or pattern recognition algorithms compare traffic parameters at a single detector station or between two detector stations against predetermined threshold values that define when incident conditions are possible. Statistical algorithms use statistical techniques to determine whether the observed detector data differ statistically from historical or defined incident conditions. Time series and smoothing algorithms compare short-term predictions of traffic conditions to measured traffic conditions. Modeling algorithms use standard traffic flow theory to model expected traffic conditions on the basis of current traffic measurements. The advanced incident detection algorithms include Fuzzy Sets, Neural Nets, Machine Vision, Automatic Vehicle Identification, and others.

A recent review of the algorithms indicated that two of the Modified California Algorithms (#7 and #8) and the McMaster Algorithms rated the highest on the basis of reported performance, operational experience, and model complexity. When calibrated properly, these algorithms can be expected to detect 70 to 85 percent of all incidents, while incorrectly triggering a false alarm about 1 percent of the time or less [63]. These algorithms were also judged to be easy to understand and implement by the operator.

2.4.2 Incident Response and Clearance

Response involves the activation, coordination and management of appropriate personnel, equipment communication links, and information media as soon as there is reasonable certainty that an incident is present. Steps in the response process include:

- Verifying the existence and location of the incident.
- Assessing the incident to determine the type of response needed to clear it.
- Initiating the appropriate response.
- Removing the incident.

A quick and timely response by the necessary resources to clear the incident can significantly reduce the incident duration and its impact on the traffic operations in the region [64].

2.4.3 Electronic Incident Management and Control Strategies

The traffic management and control components of a freeway management system are intended to help in incident management conditions. These components help to warn motorists approaching the incident location about downstream traffic conditions, advise about appropriate speeds, reduce traffic demand, and adjust control settings on other roadways to accommodate increased traffic volumes due to diversion from the freeway. The management and control components that can be used for this purpose include ramp metering and information dissemination.

Ramp metering was implemented in 1960 and showed effectiveness in reducing freeway congestion. They consist of a traffic signal to restrict motorists from entering the freeway. The traffic signals are connected to a centralized computer that control their timing based on metering control algorithms. When an incident occurs, ramp metering is implemented in real-time upstream of the incidents to restrict motorists from entering the freeway. Ramp metering typically operates during peak traffic periods, and could be adjusted if an incident occurs during these periods or during off-peak periods in case of high demand [(65)].

Information dissemination components are usually activated to warn motorists upstream of an incident about the traffic conditions ahead and inform them about which travel lanes are closed and to recommend possible diversion routes around the incident. Warning can occur through any of the different information dissemination technologies available in the region such as CMS, HAR, commercial radio, traffic reports, and others. Such information is coordinated and managed so that the information remains current especially with respect to the affected location, expected duration, and its impact on traffic conditions.

Diversion involves examining where and how much traffic should be diverted when an incident or other blockage condition occurs on any section of the freeway at any time of the day. Alternative route decisions involve determining not only where and how much traffic should be diverted, but also when diverting traffic would produce positive benefits. Since diverting traffic to alternate routes is often politically sensitive, how long a freeway is to remain closed before an official detour route is established is often a policy decision. For example, some areas divert traffic only when an incident is likely to last more than one hour. Not all arterials near a freeway may be desirable alternative routes. Examples that make an arterial not suitable as an alternative route include schools, hospitals, and sensitive neighborhoods [65].

2.5 Summary

The literature review of the different topics related to the problem under investigation showed the importance of the various ITS technologies in reducing traffic congestion and softening the impact of traffic incidents on the quality of freeway operations. Today, the various ITS components are implemented in almost all United States urban areas that are suffering from congestion. As a result, ITS assessment studies are extremely valuable to determine the magnitude of their benefits and cost and justify the public funds invested on such projects.

The MDOT ITS deployment was one of the first ITS plans of its kind. The deployment offered a unique opportunity to perform a before and after study to evaluate the effectiveness of ITS. It is unique in the sense that the deployment is relatively comprehensive, and the conditions are ideal for conducting a before and after evaluation study.

The study author chose incident based congestion during off peak hours as one of the topics to perform a before and after evaluation study. The study used average minute speed as the only traffic variable to detect incident caused congestion. Chapter 3 covers the development of the technique used to analyze the before and after data.

Chapter 3

Methodology

3.0 Introduction

The purpose of this chapter is to describe the development of the measures used to conduct the comparative study on the effectiveness of the ITS deployment program in Detroit. The measures are used to assess the incident-based congestion that occurs during off-peak hours, and rely solely on the traffic loop detector data obtained from the MITSC.

In order to test the effectiveness of the ITS deployment, three measures were established. The first measure quantifies individual station incident-based congestion. The second is a measure of the aggregate impact of individual incidents across stations. This procedure also measures the incidents' queue length and categorizes them based on this length. And finally, the third measure is an index to quantify the segment and system-wide incident-based congestion.

The following sections of this chapter have been divided into the main subjects of the methodology. The first topic is a description of the database variables and the smoothing and reconstruction functions applied to these variables. The second topic describes the establishment of the incident-based congestion speed threshold value. The third topic covers the development of the algorithm to flag the start and end of the incident-based congestion periods. The fourth part describes the algorithm established to cluster station-based congestion measures into minute-station individual incidents. The fifth and sixth topics describe the calculation of incident queue length and the procedure for categorizing segment incidents. The calculation of the segment index is included in section seven, and finally, a summary of the methodology is presented in section eight.

3.1 Description of the Database

The study utilized a traffic database obtained from the Michigan Intelligent Transportation Systems Center (MITSC) in Detroit. The traffic database came from inductive loop detectors imbedded at various locations in each freeway lane. The data included minute by minute total lane volume, average speed and occupancy, an indication of the number of lanes, and the number of lanes reporting data. The database was stored in ASCII format files and recorded on 9-track 1600 CPI magnetic tapes. The files consisted of 80 character records and the tape was written with 80 records per block. Each file contained 74,902 records of 80 characters and 12 hours of average one-minute data.

The first record on the tape was the title record, which showed the number of stations and station minutes. Following the title record, the data was organized in sets of 720 station records. Each set represented a station and covered 720 minutes of traffic data. Sets were arranged in an ascending order based on the station number. Table 3.1 shows the format of the records.

Table 3.1. Format of the traffic detector input file.

Column	Contents
1 – 4	Station number (range from 1 to 400).
6 – 11	Date in month, day, and year.
13 – 16	Four digit military time (hhmm).
18	Station type (1 = mainline, 2 = entrance ramp, and 3 = exit ramp).
20	Number of lanes (one loop per lane).
22	Number of operational lanes.
24 – 27	Total volume for all lanes (sum of all station individual loops vpm).
29 – 33	Average percentage lane occupancy.
35 - 39	Average lane speed (mph).

The traffic variables such as volume, occupancy, and speed were measured for each vehicle and computed for each lane. Volume was then summed for all lanes at a station for each minute. The unit used for volume was vehicles per minute per station. The station speed and occupancy were measured as the average one-minute speed and occupancy for all lanes, and the units for speed and occupancy were miles per hour and percent respectively. A smoothing function (equation 3.1) was then used to smooth the station one-minute volume and the average one-minute speed and occupancy.

$$\text{Speed} = \text{SPM} + G * (\text{STM} - \text{SPM}) \quad \ldots\ldots 3.1$$

Where:

Speed = Smoothed speed for the current minute.

SPM = Smoothed speed from the previous minute.

G = Tunable variable currently set at 0.20.

STM = Raw speed measured for current minute.

To obtain the smoothed occupancy and volume, the speed variables replaced by the corresponding volume and occupancy variables.

If the number of operational lanes was zero, then the value of volume, occupancy, and speed was set at –1. If the number of lanes was greater than 0 and less than the number of lanes, then the volume, occupancy, and speed were reconstructed from the operational lanes. The formula used to reconstruct volume and occupancy was:

$$(\text{Vol., or Occ.})_{\text{Reconstructed}} = \frac{\text{Number of lanes} * (\text{Vol., or Occ.})}{\text{Number of operational loops}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

Table 3.2 shows a sample of the header, and functioning, reconstructed, and malfunctioning records.

Table 3.2. Sample of a header record, and functioning, reconstructed, and malfunctioning records.

Header record	VOS-MAIN-SMOOTH				STA=285			MIN=0720	
Variable field number	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Functioning record	57	090996	0002	1	3	3	10	0.9	66.0
Reconstructed record from two stations.	59	011397	2323	1	3	2	22	2.2	64.3
Reconstructed record from one station.	78	011397	1611	1	3	1	80	12.9	41.5
Malfunctioning record	59	090996	1102	1	3	0	-1	-1.0	-1.0

The variable field numbers represented the following variables:
(1) Station ID. (2) Date.
(3) Time. (4) Station type.
(5) Number of lanes. (6) Number of reporting lanes.
(7) Volume. (8) Occupancy. (9) Speed.

3.2 Establishment of the Incident-Based Congestion's Speed Threshold Value

The primary traffic variable used in this study was the smoothed one-minute average station speed; this variable is most frequently used in describing congestion and in incident detection algorithms. To choose a speed threshold value (STHV) for flagging incidents, the related literature was reviewed and is presented in the following paragraphs.

The Highway Capacity Manual [8] Figures 3 and 4 of Chapter 4 show a gradual decrease in speed as flow increases, with an increasing rate of change of speed as capacity is approached. Speed at the border of Level of Service D and E that defines capacity is around 35 mph. The recent Highway Capacity Manual [46] revised Chapter 3 by adding new speed versus flow curves. The new version indicates that the LOS E/F breakpoint occurs at a significantly higher speed of 50 mph.

Thurgood [13], in his study of developing a freeway congestion index, stated that the onset of congestion on Utah freeways was based on traffic stream speeds falling below a threshold speed of 40 mph. His reasoning was that 40 mph falls between the new and old HCM values and the value of 40 mph is a strong indicator that flow is falling into the LOS F, where forced operation is likely to occur. He also added that a speed threshold value of 45 mph or even 50 mph would not likely have changed his results significantly because, in most cases, once the speed fell below 50 mph, they also fell below 40 mph. In contrast, Cottrell [15], in his study of measuring the extent and duration of freeway congestion in urbanized areas, chose LOS F and a speed threshold value of 35 mph as the congestion threshold value for two reasons. The first reason was based on the General Accounting Office (GAO) study [9], which found that travel delay on the Urban Interstate System was insensitive to changes in volume capacity ratio between 0.77 and 0.99. Secondly, the GAO also found that several metropolitan planning organizations and local governments, as well as the California Department of Transportation, considered a road to be congested when its volume capacity ratio was close to 1.0 with an average travel speed near 35 mph.

This paragraph reviews the research regarding the choice of speed threshold value for the McMaster Incident Detection algorithm. Forbes G. [67] used a conservative speed of 70 km/hr (43.75 m/hr) to activate his congestion logic algorithm based on the three previous studies. In the first study, Hurdle and Datta [68] identified an average speed of 80 km/hr (50 m/hr) for capacity flows. In another study, Persuad and Hall [69] identified the movement from uncongested to congested operations to be associated with a drop in speed to a value of 70 km/hr. Third, Gall and Hall [14] defined congestion data as having occupancies that exceeded a maximum uncongested threshold value of 25% and a speed threshold of 65 km/hr (40 mph).

Initially, three values of 40, 35, and 30 miles per hour were selected as the threshold value to be used in this study, then the value of 35 mph was chosen as a conservative value.

3.3 Incident-Based Congestion

The occurrence of traffic incidents on a freeway section may be reflected directly in the traffic loop detector output at that section, depending on the incident occurrence time and traffic demand. However, to quantify incident duration, it is necessary to know the time all incidents occurred and were terminated. The following subsections describe the criteria that were used to signal the start and end of incident-based congestion and the algorithm developed to determine the start, end, and duration of an incident.

3.3.1 Criteria for the Start and End of Incident-Based Congestion

In order to decide when an incident occurred and was terminated, various criteria were developed. One condition was established to define the start of incident-based congestion, and a set of five conditions were used to determine the termination of an incident. The start of incident-based congestion at any station and at any given time was flagged if the speed of the present minute and the previous three minutes was below the speed threshold value of 35 miles per hour (STHV) (provided that the station was reporting valid data).

To flag the end of incident-based congestion at a given station, five conditions were implemented, one of which was executed given that incident-based congestion had started. The first two conditions were used for the case when the present time was not noon or midnight. The first condition was for a station that was reporting valid data, and the speed during the past five minutes excluding the present minute (J) was above STHV, and the minute J-6 was below STHV. The second condition was for a station that had been reporting valid data but was starting to report invalid data. This condition was met when the station was reporting invalid data for the present minute and the past five minutes and the speed at J-6 was valid and below STHV.

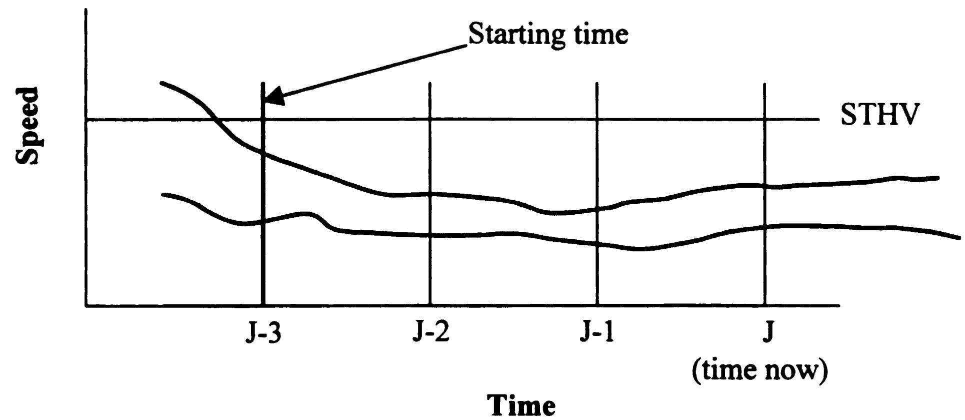
The last three conditions were developed for the case when the present time (J) was noon or midnight. The third condition was met when the station was reporting valid data with a speed below the STHV at the present minute and during the past 6 minutes. The fourth condition was met when the station was reporting valid data and the speed changed to above the STHV at any time during the past five-minute period. Finally, the fifth condition was met when the speed was below the STHV and the station started to report invalid data at any time during the previous five minutes. Figure 3.1 illustrates the condition for the onset of incident-based congestion and the five conditions to signal the end of incident-based congestion.

3.3.2 Development of the Incident-Based Congestion Periods

This subsection describes the development of an algorithm to apply the criterion established in section 3.3.1 to each of the station's data. The algorithm started by allocating memory for an array of 720 objects to store one set of station data, and each object had member variables to store the values of the traffic detector variables. The 720 objects were used for all station sets. The algorithm also allocated memory for an array of objects to store variables required for the functional and malfunctional detector incident-based congestion periods. Other arrays of objects were also allocated to store the periods of incident-based congestion that occurred during the pre-peak, post-peak, and peak hours.

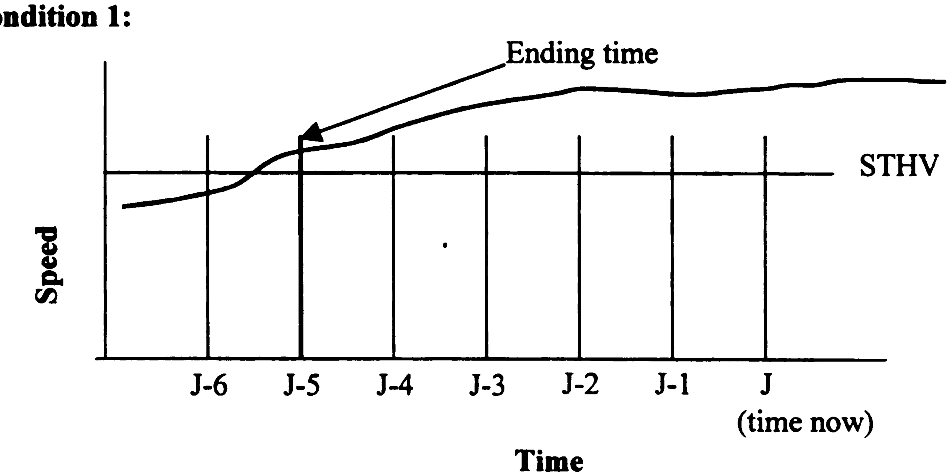
The algorithm read the input file and once it reached a station that belonged to any of the study segments, it recorded the station's 720 minutes of information in the proper objects allocated earlier in memory. Then it looped twice through the 720 objects. The first loop involved the process of searching for periods of incident-based congestion, and the second involved the search for periods of malfunctioning data. During the first loop, the objects were checked if the condition for the start of congestion was satisfied; in this case, it opened a functional object and stored the starting time of the incident. The algorithm then continued the loop until one of the five conditions for the end of congestion was satisfied, in which case it recorded the incident ending time and

Criterion used to define the onset of incident congestion:



Criteria used to define the end of congestion:

Condition 1:



Condition 2:

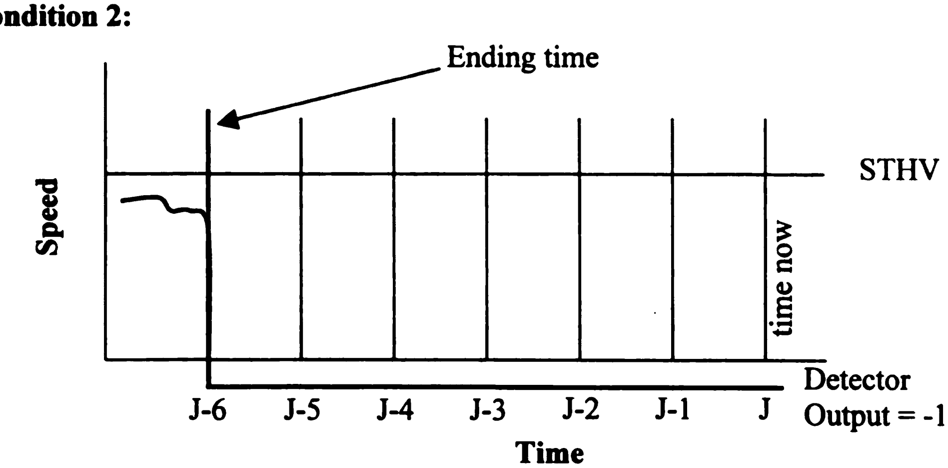
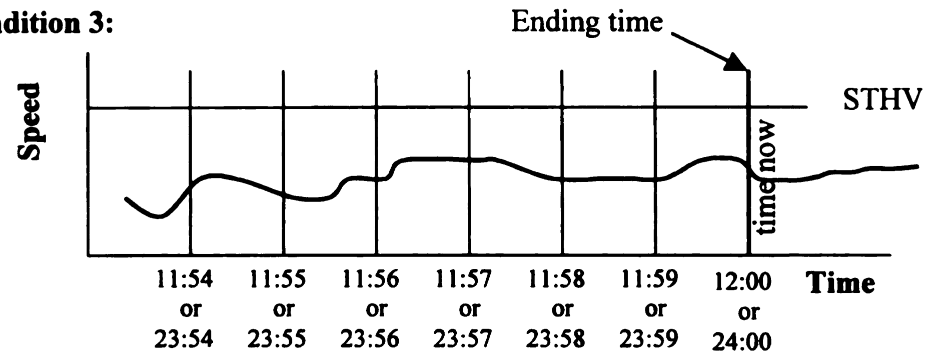
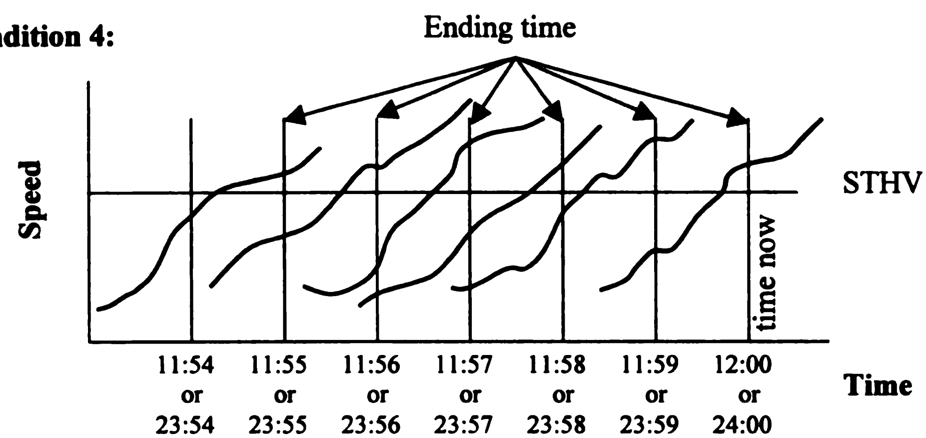


Figure 3.1. Criteria for the start and end of station incident-based congestion.

Condition 3:



Condition 4:



Condition 5:

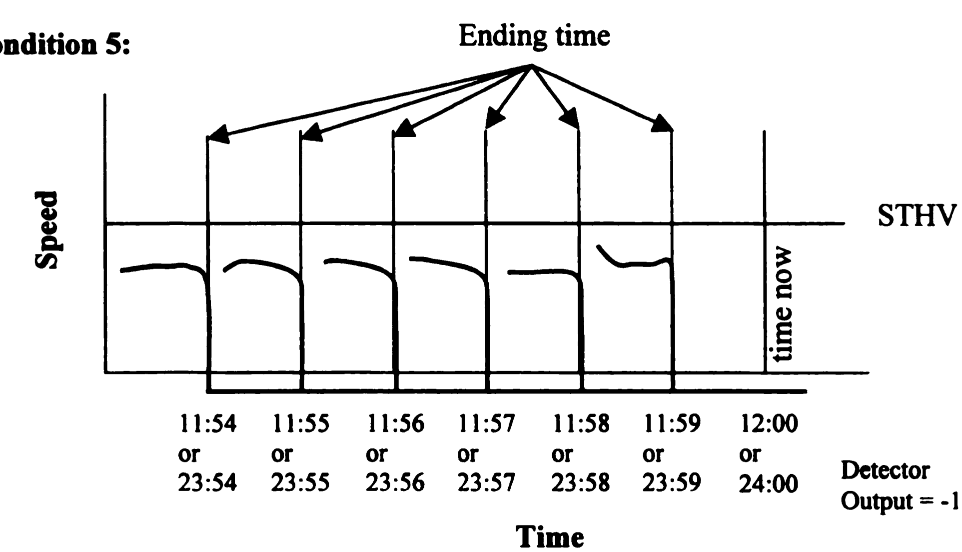


Figure 3.1 (cont.). Criteria for the start and end of station incident-based congestion.

calculated the incident duration. It continued looping through the remaining 720 objects repeating the same checks looking for other incidents that might have occurred during the remainder of the 12-hour period.

During the second loop, the algorithm looked for periods of invalid data. There were no conditions established to start or end these periods. The algorithm went through the station set of data looking for such periods. Once a station was detected reporting invalid data, a malfunctioning object was opened and the starting time, ending time, and duration of the failure period were recorded. Then it continued looping to the next period following the same procedure until it finished looping through the 720 objects. The algorithm then proceeded to the next relevant station and performed the same steps.

After the end of the input file was reached, the physical location for each station in the functioning and malfunctioning objects was added to their objects. The periods of the functioning and malfunctioning objects were then divided into pre-peak, post-peak, and peak periods. The functional and malfunctional objects for each of the three periods were combined and their values were stored in the objects previously allocated in memory. Figures 3.2, and 3.3 depict a flow chart illustrating the algorithm's steps and periods of congestion for various stations versus time.

3.4 Clustering Station Incident-Based Congestion Periods

The impact of an incident can be detected at single or multiple stations, depending on the incident severity and the level of traffic demand. The previous section described a procedure to determine estimated individual station incident starting and ending times

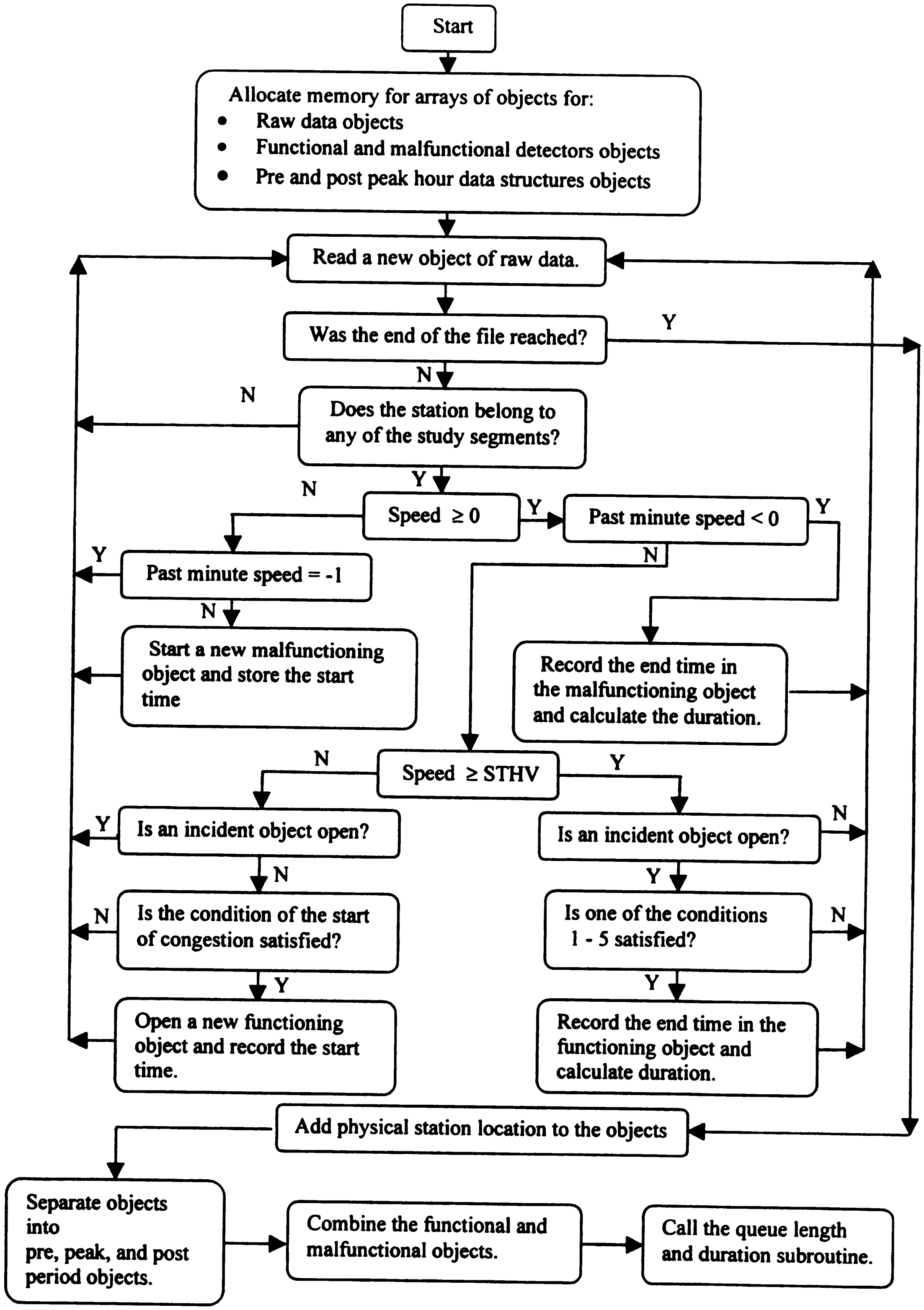


Figure 3.2. Flow chart for the station incident-based congestion.

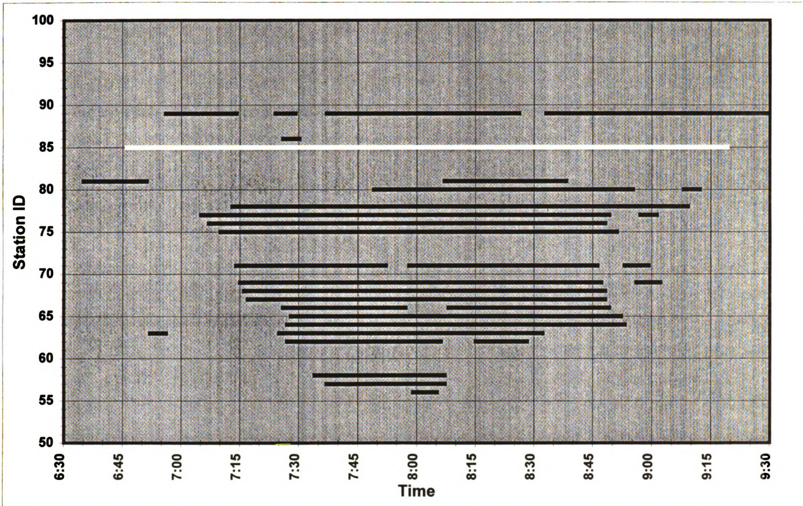


Figure 3.3 Duration of congestion on WB I-94, Mon. 7/24/95. (Dark < 35 mph, White = No data)

and duration. This section describes the criteria and procedure developed to cluster related stations in the case of severe incidents where multiple stations are affected.

3.4.1 Criteria for Clustering Station Incident-based Congestion Periods

To determine the grouping of the incident-based congestion periods obtained from individual stations, three conditions were developed. The three conditions are depicted in figures 3.4, 3.5, and 3.6. Condition one was set when two incident-based congestion periods ab and cd belonged to two adjacent stations. In this case, the two were grouped into one incident if one of the following conditions was satisfied:

$c \leq a \leq d$ 3.3

$c \leq b \leq d$ 3.4

$e \leq g \leq f$ 3.5

$e \leq h \leq f$ 3.6

Where:

a, c, e, and g are the starting time of incident-based congestion at stations 1, 2, and 3 and b, d, f, and h are their corresponding ending times.

The second condition was established for a station that had two congestion periods separated by a variable named endstart, which is the time between the end of congestion period 1, and the start of congestion period 2. If the value of endstart is ≤ 15 minutes then the second congestion period is added to the first incident. The third condition dealt with the case where successive stations had malfunctioning detectors; in this case a maximum of 3 successive malfunctioning stations that were enclosed in functioning stations were allowed in each incident.

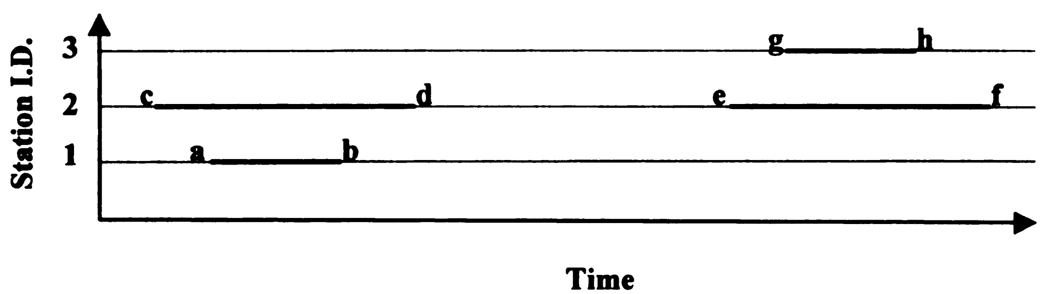


Figure 3.4. Clustering successive stations of incident-based congestion (Case 1).

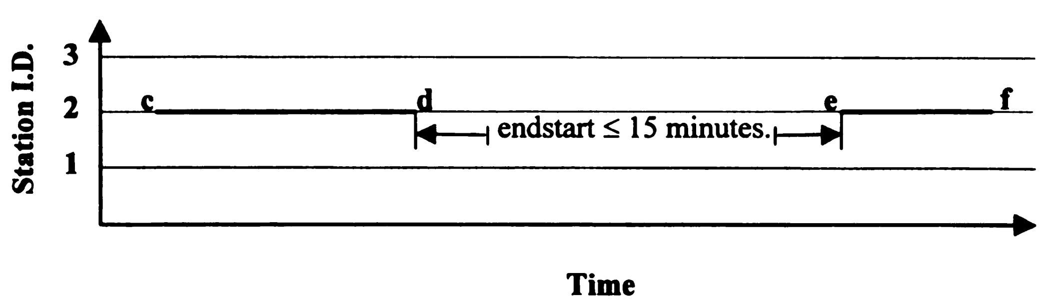


Figure 3.5. Clustering periods of incident congestion belonged to the same station (Case 2).

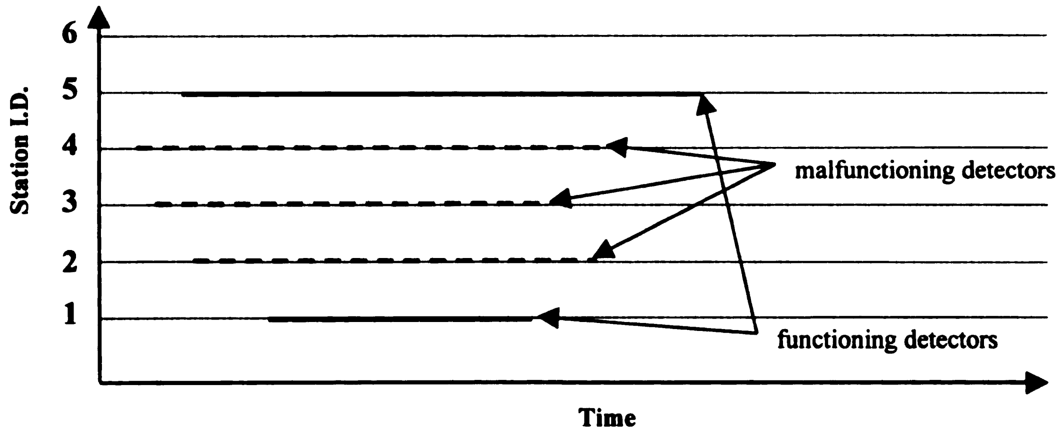


Figure 3.6. Clustering malfunctiong stations (Case 3).

3.4.2 Development of the Clustering Technique

This subsection describes the development of the procedure used to cluster related station congestion periods by applying the criteria presented in section 3.4.1. The procedure was performed in three steps. The first step began by calculating the number of congestion periods in each segment, then the algorithm performed three imbedded loops. The outer loop looped the number of segments, the middle loop looped the number of incidents reserved once the program started executing, and the inner most loop looped the number of periods in each segment. After starting the first pass in each of the three loops, the algorithm read the first period in the segment; if the period belonged to a malfunctioning period it was skipped and the second pass was performed. This process continued until a functioning period was encountered; at that time the routine opened the first incident object and stored the period's information in its first array element of the incident period objects. It then moved to the next period and determined whether the period belonged to an adjacent downstream station or the same station (conditions established in sec 3.4.1); if the conditions were satisfied, the period was clustered in the subsequent element of the incident object. It continued looping through the segment period's objects and marked those that were clustered. The same procedure was performed for all other segments. The unmarked periods were clustered during the second and third passes. Figure 3.7 shows the flow chart of the program written to accomplish the first step.

The following two steps involved clustering the periods of incident-based congestion periods that were missed in the first pass. The algorithm was called after the conditions on closing an incident were satisfied. The algorithm received the address in memory of the incident objects and the incident-based congestion period objects as well as the segment number and the starting and ending period numbers in the segment. The algorithm performed two loops: the outer loop that looped the number of periods in the segment and the inner loop that looped the number of periods in the incident. The outer loop started by reading the first unmarked period in the segment and determined the upstream station ID. It then looped through the incident periods to determine whether the period fell upstream from the segments unmarked period; if this condition was satisfied, the clustering conditions in section 3.4.1 were checked. If these conditions were satisfied, the segment period was added to the incident and marked. The program then moved to the next unmarked period and performed the same checks. It continued looping through the remaining segment periods and performed the same checks. Figure 3.8 illustrates the flow chart for the steps described above.

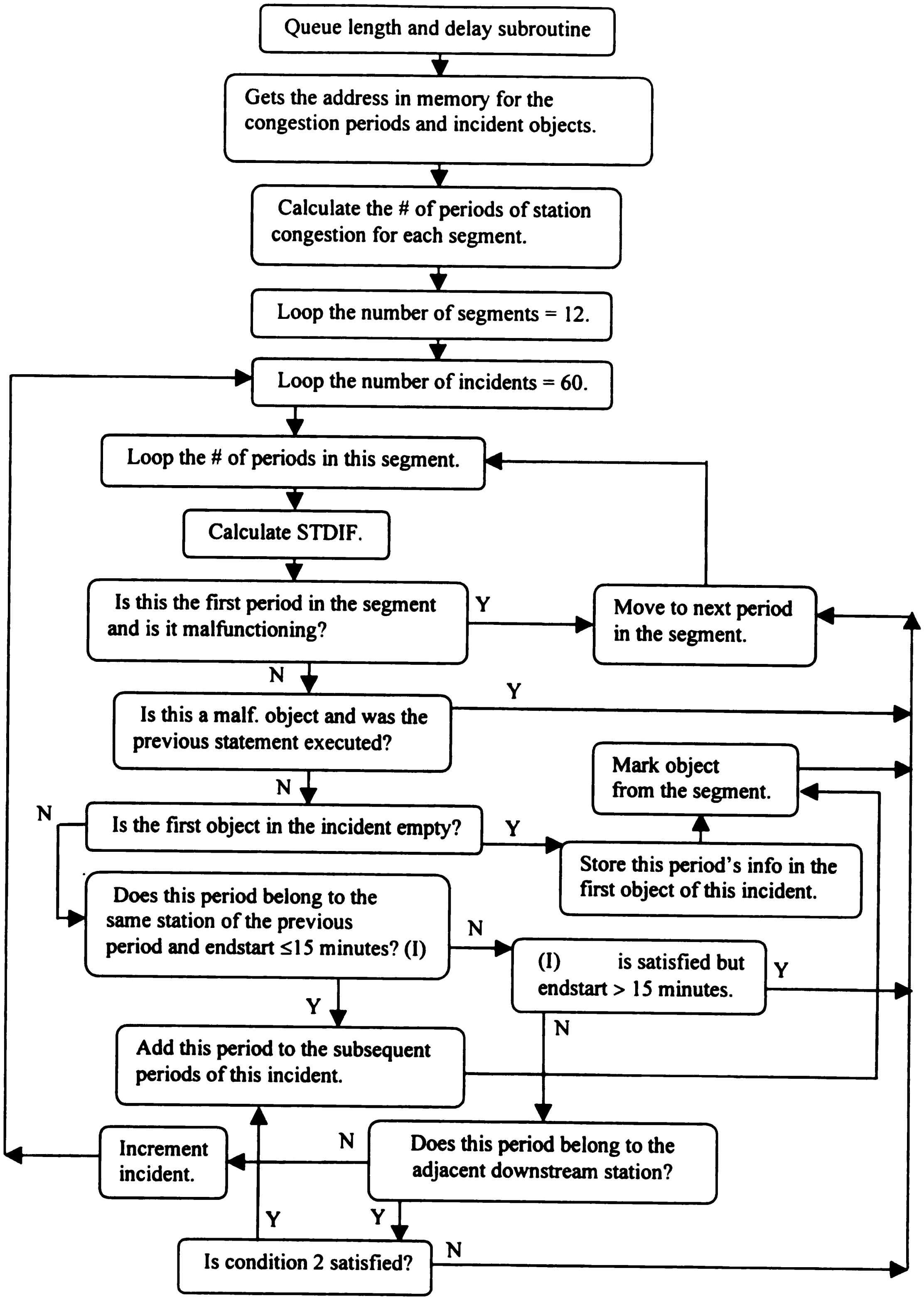


Figure 3.7. Flow chart for the first pass algorithm.

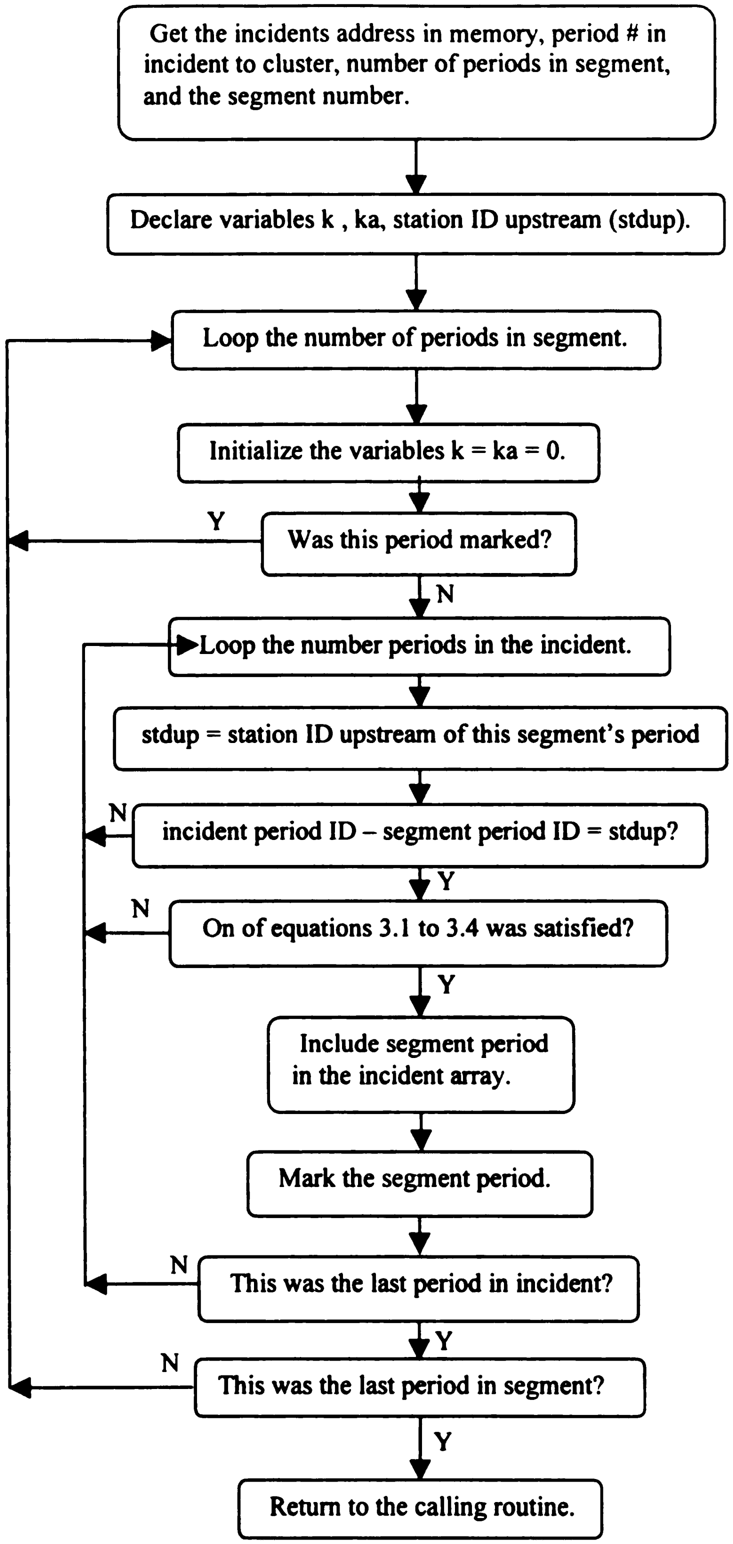


Figure 3.8. Flow chart for the subroutine second pass algorithm.

The last step had a structure almost identical to step two. In this step, the missed periods in the segment were checked if they fell downstream from any of the incident periods. Those periods were clustered if any of the conditions of section 3.4.1 were satisfied. The algorithm received the same addresses in memory as step two. Figure 3.9 shows the flow chart for the third part.

To test the performance of the clustering techniques, incidents that occurred at different times and dates during the months of July and November of 1995 were collected in files and tested. Figure 3.10 shows one of the incident files used for this purpose. The incident time shown in the figure is not the actual time and day when the incidents occurred.

Figure 3.10 illustrates ten different incidents of various lengths and characteristics. They can be categorized into two groups; the first group required only the first part of the clustering algorithm due to their simple pattern, and the second group required the second or third or both parts to cluster. The first group is represented by incidents 1, 2, 3, 4, 7, 8, and 10. The effect of incidents 1, 3, 7, and 10 was observed on one station and each had one period of incident-based congestion except incident 3, which had two periods that were 7 minutes apart. Incident 4 had three periods of functioning stations. The last incidents of this category were 2 and 4, which had multiple periods and included malfunctioning stations. The second group of incidents is represented by incidents 5, 6, and 9. Incidents 6 and 9, each had one period, 6-1 and 9-1, that were missed on the first pass; these periods were clustered during the second and third pass algorithms respectively. Incident 5 had two periods, 5-1 and 5-2, that were missed on the first pass and were clustered during the second and third pass algorithms.

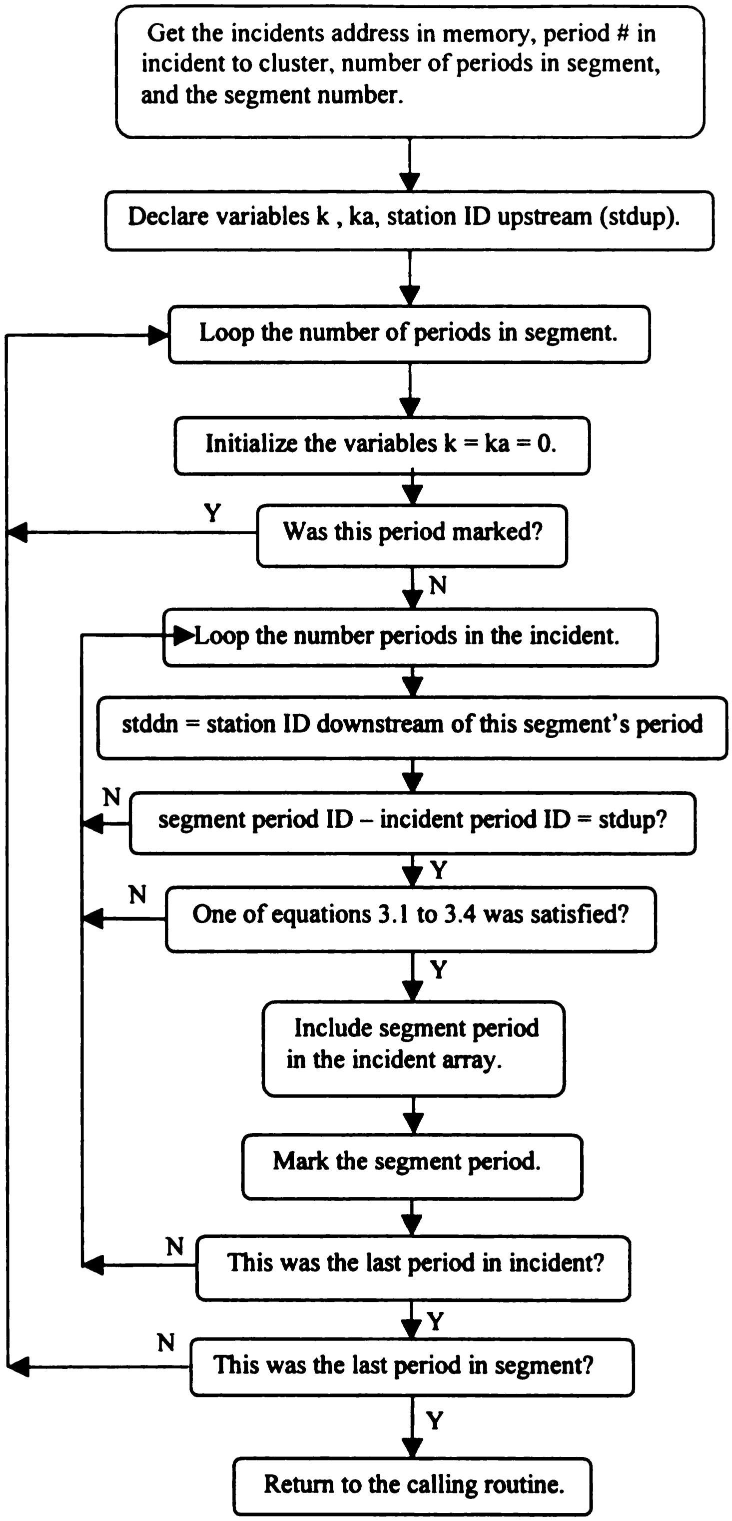


Figure 3.9. Flow chart for the subroutine third pass algorithm.

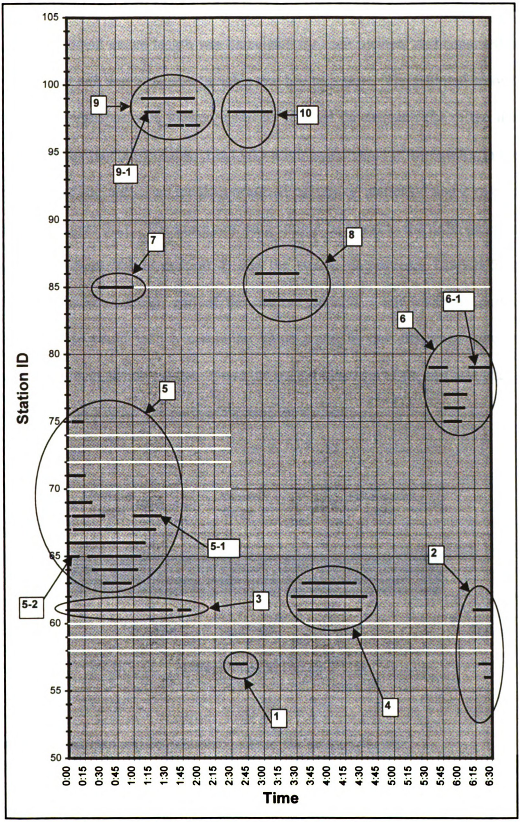


Figure 3.10 Incident samples

3.5 Incident Queue Length

The incident queue length was calculated for each incident and consisted of two parts. The first part was a random variable that had two parts. The first and second parts of the random variable were located upstream (l_u) and downstream (l_d) of the incident. Both parts of the random variable could take a minimum value of zero miles in the case where the front and rear of an incident occurred exactly on stations 4 and 2 respectively as shown in Figure 3.11. The maximum value might be equal to the difference between the incident's front station (station 4) and the station downstream (station 5) of the incident for the downstream part of the random variable. The upstream part of the random variable could take a maximum value equal to the difference between the incident's upstream station (station 2) and the station upstream of the incident (station 1). Figure 3.11 illustrates the two parts of the random variable.

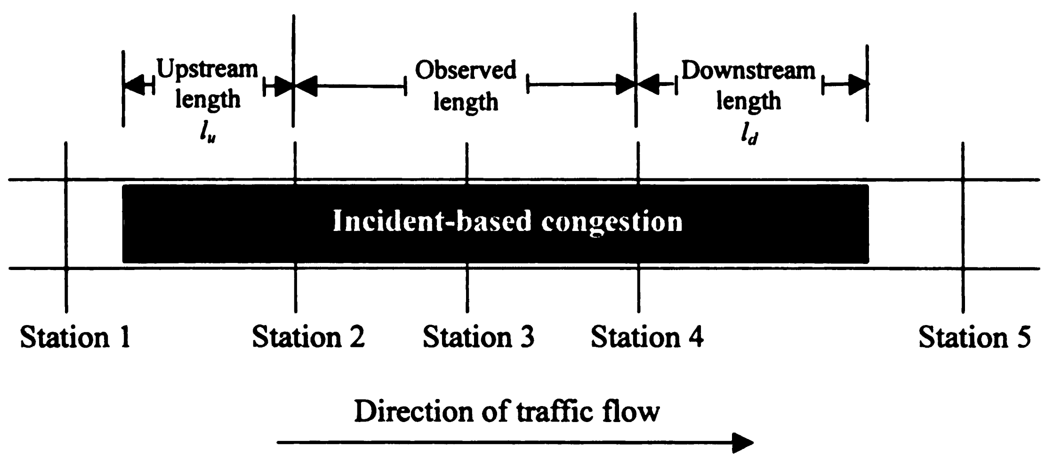


Figure 3.11 Upstream and downstream parts of the random variable.

The second part of the incident queue length involved a numerical calculation that was a result of the clustering technique developed in section 3.4. A routine was written to locate the incident's extreme upstream and downstream stations, and the queue length was then determined by calculating the difference in miles between the upstream and downstream locations. Figure 3.12 shows the flow chart of the subroutine written to perform the queue length numerical calculation.

3.6 Categorizing Segment Incidents

Once the incident queue length was calculated, the segment was categorized based on this length. The first incident category was for incidents that had a length of a random variable L, and the subsequent categories were lengths incremented by 0.5 miles. The shortest incident fell in category one with a queue length equal to a random variable L, and the longest fell in category eight, which had a length of more than 3 miles. Then the number of incidents within each category was calculated. Table 3.3 shows the different categories of incident queue lengths and Figure 3.13 illustrates the flow chart used to accomplish these steps.

Table 3.3. Categories of incident queue lengths.

Category number	**Incident queue length (miles)**
1	L
2	(0.0 ≤ Incident Queue Length ≤ 0.5) + L
3	(0.5 ≤ Incident Queue Length ≤ 1.0) + L
4	(1.0 ≤ Incident Queue Length ≤ 1.5) + L
5	(1.5 ≤ Incident Queue Length ≤ 2.0) + L
6	(2.0 ≤ Incident Queue Length ≤ 2.5) + L
7	(2.5 ≤ Incident Queue Length ≤ 3.0) + L
8	Queue Length ≥ 3.0

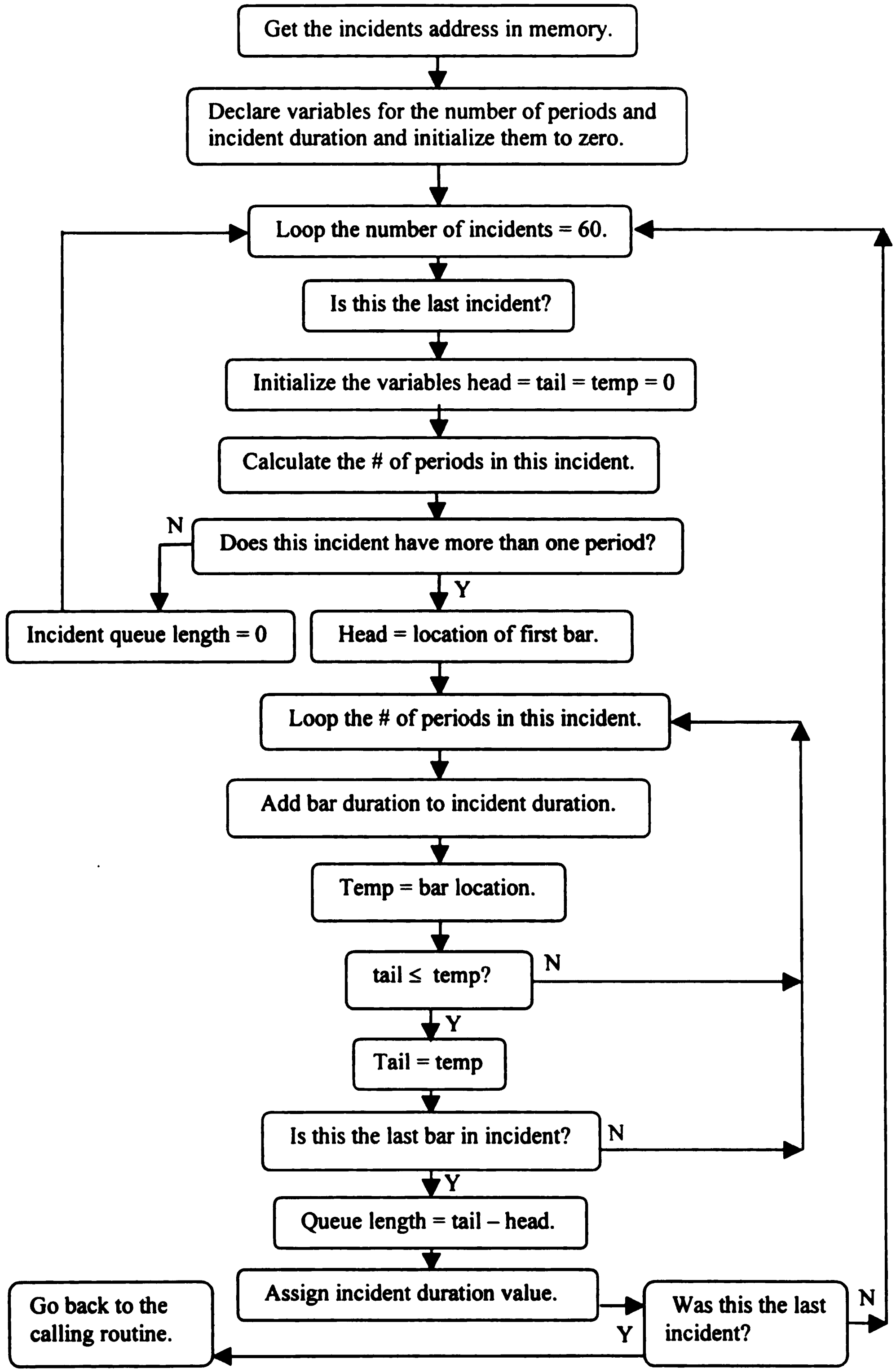


Figure 3.12. Flow chart for the queue length of incident-based congestion.

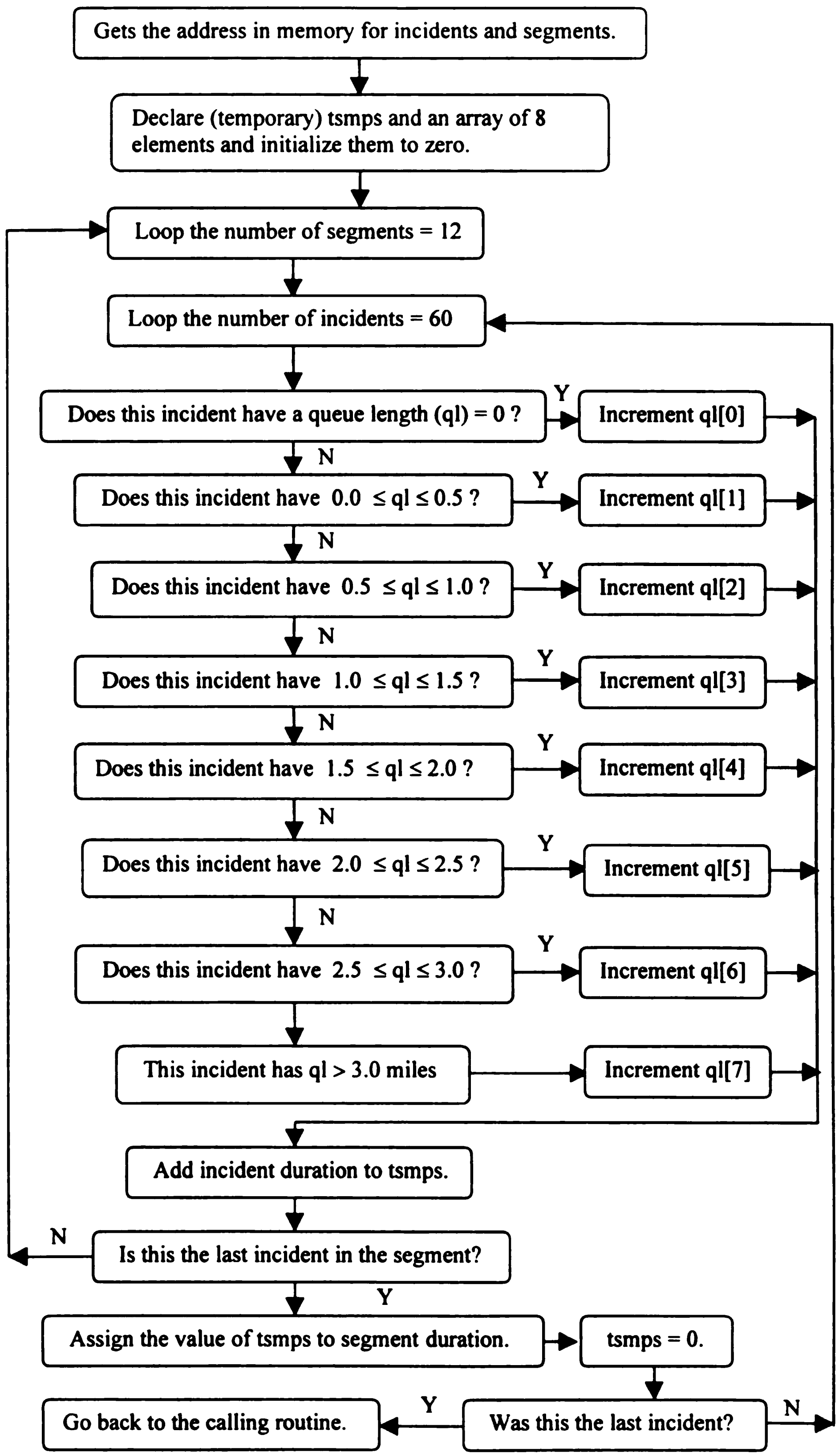


Figure 3.13. Flow chart for the queue length subroutine.

3.7 Incident-based Congestion Index

The final measure developed was the station, segment, and network incident-based congestion index. This index is a measure of the time a station, segment, or the network is congested due to incidents. The index is used to estimate the average daily minutes of incident-based congestion by multiplying the index value times the number of off-peak daily minutes. Equations 2, 3, and 4 define the station, segment, and network incident-based congestion indices. The denominator in equation 1 represents the number of the station off-peak minutes in the sample. This number was multiplied by the number of stations in the segment or the network as a whole for equations 3 and 4 respectively. Figure 3.14 illustrates the flow chart used to calculate the segment index.

$$STIBCI = \frac{\sum_{in=1}^{in=n} ID}{NOSTM} \qquad 3.7$$

$$SGIBCI = \frac{\sum_{sn=1}^{sn=m} \sum_{in=1}^{in=n} ID}{NOSGS} \qquad 3.8$$

$$NIBCI = \frac{\sum_{sgi=1}^{sgi=12} \sum_{sn=1}^{sn=m} \sum_{in=1}^{in=n} ID}{NONSM} \qquad 3.9$$

where;

STIBCI	= Station incident-based congestion index
SGIBCI	= Segment incident-based congestion index
NIBCI	= Network incident-based congestion index
sgi	= Segment number
sn	= Station number
m	= Maximum number of stations on the segment

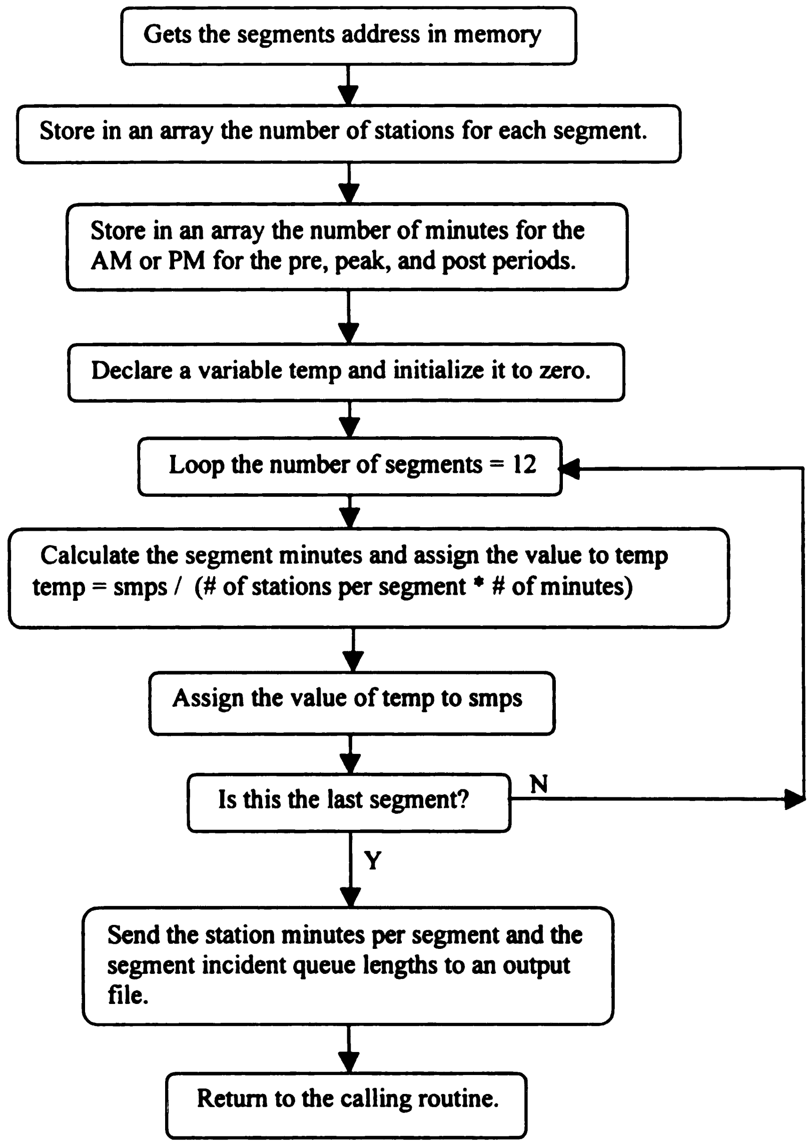


Figure 3.14. Flow chart for the subroutine the station minutes per segment.

in	= Incident number
n	= Maximum number of incidents that occurred on the station
ID	= Incident duration
NOSTM	= Length of observation period at a station (minutes)
NOSGSM	= Length of observation period on a segment (minutes)
NONSM	= Length of observation period on the network(minutes)

3.8 Summary

The methodology demonstrates the development of the different measures of effectiveness to evaluate the ITS deployment program based on incident-based congestion. The performance of the measures was tested using a sample file that included incidents that occurred during the months of July and November of 1995. The algorithm identified all of the incidents.

The measures of effectiveness can be used to compare non-recurring congestion before and after ITS technologies are implemented. Implementing the ITS is intended to reduce the impact of incidents by reducing the traffic demand through ramp metering and diverting traffic to adjacent streets with available capacity by using CMS. This claim can be verified by studying the change in the magnitude of the incident-based congestion index and the change in incident queue length. Chapter 4 covers the analysis of the traffic data using the methodology developed in this chapter.

Chapter 4

Analysis and Results

4.0 Introduction

The analysis of the traffic data gathered before the ITS deployment program became fully operational was conducted using the research methodology developed and described in Chapter 3. The analysis was performed to accomplish four primary goals: first, to estimate the station and segment monthly variation in the incident-based congestion index; second, to estimate the monthly and segment variation in incident frequency; third, to estimate the distribution of the monthly incident queue length and frequency. And finally, to develop a plan to conduct the after analysis.

Chapter 4 is divided into sections that describe the steps followed to analyze the traffic data. The first section describes the network study segments and the second section presents the variation in traffic volume during off-peak hours. The third section explains the method used to process a single traffic file and how the single processed output files were integrated to yield monthly output files. The fourth and fifth sections describe the station and segment monthly variation of the incident-based congestion index and frequency, respectively. The sixth section presents the plan to conduct the after analysis, and finally the chapter summary is included in section seven.

4.1 Description of the Study Segments

Two freeways (I-94 and M-10) were considered in this study. To help isolate locations with high incident-based congestion and incident frequency, each direction of the two freeways was divided into three segments of various lengths. The first segment on each freeway is that portion of the freeway that would carry traffic destined for the central city in the morning peak period. The second segment is that portion of each freeway in the central city, and the third segment is the portion of the freeway that carries the heavy outbound traffic in the evening peak period. Table 4.1 contains detailed information concerning the study segments, including segment length and types of ITS components and Figure 4.1 shows the location of the segments on the map of Detroit.

4.2 Processing the Traffic Data

The database included 180 files representing nine months of traffic data and each file contained 12 hours of either AM or PM minute by minute traffic data. Each data set consisted of ten consecutive working days. The database processing procedure was performed in two steps and this section is divided into two subsections describing the steps. The first subsection describes the output file of a single processed file and the second presents the method used to integrate single output files to form monthly output files. Table 4.2 shows the months and dates of each of the nine sets of traffic data.

Table 4.1. Segment description.

Segment Number	Station ID	Freeway	Segment Length (Miles)	Number of detectors	Number of CMS	Number of ramp meters	Number of CCTV	Number of HAR	Starting reference road	Ending reference road
1	54-82	WB-I94	7.54	29	1	9	-	1	Morross	Chene
2	83-96	WB-I94	2.62	11	1	1	2	-	I-75	I-96
3	98-108	WB-I94	2.84	10	-	1	1	-	Grand Blvd.	Wyoming
4	109-123	EB-I94	2.74	13	1	2	-	-	Wyoming	Grand Blvd
5	125-141	EB-I94	2.73	11	-	3	1	-	Grand Blvd.	I-75
6	142-173	EB-I94	2.41	28	-	8	-	-	I-75	Morross
7	177-192	NB M-10	2.36	10	2	5	-	1	Howard	Milwaukee
8	193-204	NB M-10	2.38	10	-	3	-	1	Grand Blvd.	E. Davison
9	205-225	NB M-10	5.79	21	1	4	-	1	W. Davison	Greenfield
10	226-245	SB M-10	5.92	20	-	4	-	-	Greenfield	W. Davison
11	246-260	SB M-10	2.73	11	1	4	-	-	Davison	Milwaukee
12	261-274	SB M-10	2.73	10	2	5	4	-	Milwaukee	Howard

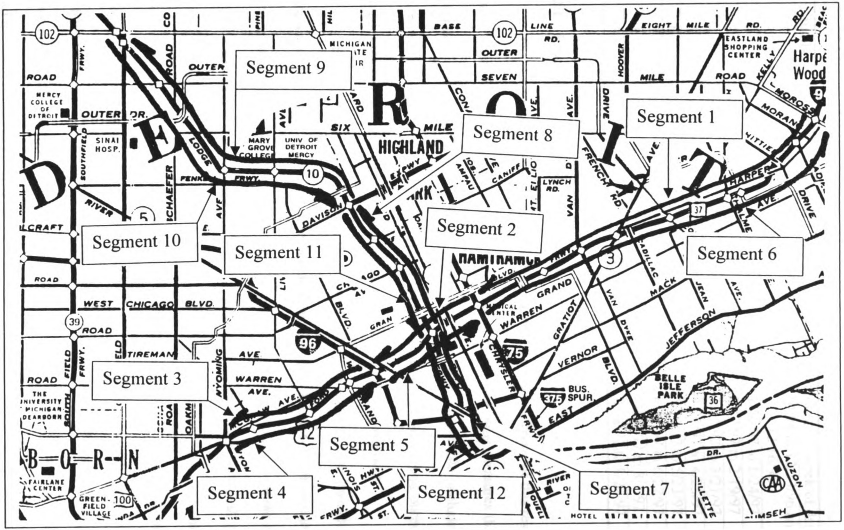


Figure 4.1. Study sgements on the map of Detroit.

Table 4.2 Months and dates of the traffic data sets.

Set number	Month	Dates of 1st week of data	Dates of 2nd week of data
1	Dec. 96	12/3/96 to 12/6/96 and 12/9/96	12/10/96 to 12/13/96 and 12/16/96
2	Jan. 97	1/13/97 to 1/17/97	1/20/97 to 1/24/97
3	Feb. 97	2/10/97 to 2/14/97	2/17/97 to 2/19/97
4	Mar. 97	3/10/97 to 3/14/97	3/17/97 to 3/21/97
5	Apr. 97	4/14/97 to 4/18/97	4/21/97 to 4/25/97
6	May 97	5/12/97 to 5/16/97	5/19/97 to 5/23/97
7	Jun. 97	6/16/97 to 6/20/97	6/23/97 to 6/27/97
8	Jul. 97	7/21/97 to 7/25/97	7/28/97 to 8/1/97
9	Aug. 97	8/11/97 to 8/15/97	8/18/97 to 8/22/97

4.2.1 Processing a Single Traffic Data File

The output of a single processed traffic data file was the backbone of this research study. There are two major output files formatted to provide the basic measures that are integrated later to yield the monthly measures. The first output file includes the estimated incident-based congestion periods for each station and the second output file includes the estimated incident frequency and queue length for each segment.

The first output file consists of three major parts, and each has four variables: the duration of the pre-peak incident-based congestion and its associated traffic volume for each station, and the total number of reported minutes and its associated volume during the pre-peak period for each station. The second part includes the post-peak period values of the same variables as in part one. The number of reported minutes at each station was used to estimate the value of the make-up factor for each station during the pre-peak and post-peak periods. The make-up factors were then used to factor the entries in parts one and two and summed to yield the entries of part three. Table 4.3 shows these three major parts for segment 5 during the AM period on January 13, 1997. The PM files had the same format as the AM files and the daily measures were obtained by adding the

Table 4.3 Single file of the duration of incident-based congestion for 1/13/97, AM

	Time											
	(1) 00:00 to 06:30				(2) 09:30 to 12:00				(3) 00:00 to 12:00 (factor			
St_id	Con_t	Con_v	Rep_t	Rep_v	Con_t	Con_v	Rep_t	Rep_v	Con_t	Con_v	Rep_t	Rep_v
125	0	0	390	8803	0	0	129	9256	0	0	519	19566
126	0	0	390	7074	0	0	129	7913	0	0	519	16275
128	0	0	390	10247	0	0	129	10144	0	0	519	22042
129	0	0	390	9865	0	0	129	9995	0	0	519	21487
131	0	0	390	10621	0	0	129	8892	0	0	519	20961
133	0	0	390	10555	0	0	129	8281	0	0	519	20184
134	0	0	390	10135	29	1472	129	7459	34	1712	519	18808
137	0	0	390	8095	16	1304	129	8289	19	1516	519	17733
138	0	0	390	7997	0	0	129	7462	0	0	519	16674
139	0	0	390	7613	0	0	129	6783	0	0	519	15500
141	0	0	0	0	0	0	0	0	0	0	0	0

St_id Station ID
Con_t Duration of incident-based congestion (min.)
Con_v Volume involved in incident-based congestion (vehicles)
Rep_t Detector total reporting time (min)
Rep_v Total reporting volume (vehicles)

AM and PM files. Table 4.4 shows the duration of incident-based congestion for segment 5 on 1/13/1997

The second output file, shown in Table 4.5, includes the frequency of the different incident queue length categories for each segment for the AM period of 1/13/1997. The station make-up factor obtained in the first output file was used to estimate the segment make-up factor for each off-peak period. The segment make-up factor was then applied to the observed incident frequency in Table 4.5 to yield the entries in table 4.6. The PM files had the same format as the AM files and the daily incident frequencies were obtained by adding the AM and PM files. Table 4.7 shows the incident frequencies for 1/13/1997.

4.2.2 Integration of Multiple Traffic Output Data Files

This subsection describes how the 20 output files that belonged to each set (month) of traffic data were integrated to form an output file. The periods of incident-based congestion were summed over the 20 files and the incident-based congestion index was calculated for each station. Similarly, the incident frequency and incident queue length categories were summed for each segment to yield the monthly segment incident frequency with their corresponding queue length. Table 4.8 and Table 4.9 show the monthly values of the station incident-based congestion index for segment 5 and the segment incident frequency for the month of January 1997, respectively. The same procedure was followed in processing the other eight months. The following sections describe the utilization of the monthly output files to achieve the goals listed at the beginning of this chapter.

Table 4.4 Duration of incident-based congestion for 1/13/97

	Time											
	(1) 00:00 to 12:00				(2) 12:00 to 00:00				(3) 1/13/1997			
St_id	Con_t	Con_v	Rep_t	Rep_v	Con_t	Con_v	Rep_t	Rep_v	Con_t	Con_v	Rep_t	Rep_v
125	0	0	519	19566	15	1295	527	34055	15	1295	1046	53621
126	0	0	519	16275	18	1440	527	27847	18	1440	1046	44123
128	0	0	519	22042	0	0	527	35443	0	0	1046	57486
129	0	0	519	21487	0	0	527	33793	0	0	1046	55280
131	0	0	519	20961	0	0	527	34323	0	0	1046	55283
133	0	0	519	20184	0	0	527	32895	0	0	1046	53079
134	34	1712	519	18808	0	0	527	31017	34	1712	1046	49826
137	19	1516	519	17733	0	0	527	32817	19	1516	1046	50550
138	0	0	519	16674	0	0	527	32636	0	0	1046	49310
139	0	0	519	15500	0	0	527	31309	0	0	1046	46809
141	0	0	0	0	0	0	0	0	0	0	0	0

St_id Station ID
Con_t Duration of incident-based congestion (min.)
Con_v Volume involved in incident-based congestion (vehicles)
Rep_t Detector total reporting time (min)
Rep_v Total reporting volume (vehicles)

Table 4.5 Single file output of incident frequency and queue length for 1/13/97, AM

Time	Segment number	Queue length (miles) L	0.0 to 0.5 + L	0.5 to 1.0 + L	1.0 to 1.5 + L	1.5 to 2.0 + L	2.0 to 2.5 + L	2.5 to 3.0 + L	> 3.0 + L
0:00 to 6:30	1	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0
	4	1	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0
	7	2	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0
	12	2	0	0	0	0	0	0	0
9:30 to 0:00	1	0	0	0	0	0	0	0	0
	2	1	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0
	5	0	2	0	0	0	0	0	0
	6	1	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0	0

Table 4.6 Single file output of factored incident frequency and queue length for 1/13/97, AM

			Queue length (miles)							
Time	Segment number	Make Up Factor	L	0.0 to 0.5 + L	0.5 to 1.0 + L	1.0 to 1.5 + L	1.5 to 2.0 + L	2.0 to 2.5 + L	2.5 to 3.0 + L	> 3.0 + L
0:00 to 6:30	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	1.00	1	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	1.00	2	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0	0
	12	1.00	2	0	0	0	0	0	0	0
9:30 to 0:00	1	0	0	0	0	0	0	0	0	0
	2	1.16	1	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	1.16	0	2	0	0	0	0	0	0
	6	1.16	1	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0	0	0

Table 4.7 Factored incident frequency and queue length for 1/13/97

	Queue length (miles)							
Segment number	L	0.0 to 0.5 + L	0.5 to 1.0 + L	1.0 to 1.5 + L	1.5 to 2.0 + L	2.0 to 2.5 + L	2.5 to 3.0 + L	> 3.0 + L
1	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	2	0	0	0	0	0	0	0
5	0	3	0	0	0	0	0	0
6	2	0	0	0	0	1	0	0
7	2	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	2	0	0	0	0	0	0	0

Table 4.8 Duration of incident-based congestion for January 1997

St_id	Con_t	Con_v	Rep_t	Rep_v	IBCI	DOIBC
125	25	2189	10758	456706	0.231	2.5
126	49	3385	10759	351008	0.455	4.9
128	35	2963	9523	523071	0.362	3.9
129	0	0	9523	515097	0.000	0.0
131	0	0	10759	548021	0.000	0.0
133	0	0	10759	527945	0.000	0.0
134	43	2246	10759	504585	0.397	4.3
137	33	2379	10501	497453	0.310	3.4
138	0	0	10759	506240	0.000	0.0
139	0	0	10759	469541	0.000	0.0
141	0	0	0	0	0.000	0.0
Total	184	13161	104859	4899669	0.175	1.9

St_id	Station ID
Con_t	Duration of incident-based congestion (min.)
Con_v	Volume involved in incident-based congestion (vehicles)
Rep_t	Detector total reporting time (min)
Rep_v	Total reporting volume (vehicles)
IBCI	Incident-based congestion index
DOIBC	Duration of daily incident-based congestion per station

Table 4.9 Incident frequency and queue length for January, 1997

Segment number	Queue length (miles)							
	L	0.0 to 0.5 + L	0.5 to 1.0 + L	1.0 to 1.5 + L	1.5 to 2.0 + L	2.0 to 2.5 + L	2.5 to 3.0 + L	> 3.0 + L
1	2	1	0	1	1	0	0	0
2	3	2	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0
4	15	0	0	0	1	0	0	0
5	2	6	0	0	0	0	0	0
6	9	0	1	0	0	1	0	0
7	2	0	0	0	0	0	0	0
8	4	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	15	0	1	0	0	0	0	0
11	0	1	1	0	0	0	0	0
12	12	4	1	0	0	0	0	0

4.3 Incident-based Congestion Index

This section presents the incident-based congestion index obtained by processing the nine sets of traffic data described in section 4.2. Tables 4.10 to 4.13 show the estimated average values of the incident-based congestion index by month and season for each station. Table 4.14 includes the values of the estimated incident-based congestion index for the different months and segments. The values of the incident-based congestion index included in these tables are utilized to determine the stations, months and segments with high incident-induced congestion.

This section is divided into four subsections. The first subsection presents the average monthly and seasonal station incident-based congestion index. The second subsection presents the monthly variation in the incident-based congestion index by segment. The third subsection includes the segment by segment variation in the incident-based congestion index and the last subsection describes the system wide monthly variation in the incident-based congestion index.

4.3.1 Station incident-based Congestion Index

The average monthly station incident-based congestion index by season are included in Tables 4.10 to 4.13. These Tables are plotted in Figures 4.2 to 4.5. and analyzed in the following subsections.

4.3.1.1 Station incident-based Congestion Index on WB I-94

Figure 4.2 shows the seasonal variation in the incident-based congestion index for segments 1, 2, and 3 on WB I-94. In the winter, segment 1 showed low values of

Table 4.10 Average monthly station incident-based congestion index

Station ID	IBCI	Station ID	IBCI	Station ID	IBCI	Station ID	IBCI
54	0.023	105	0.049	163	0.049	221	0.000
55	0.036	106	0.011	164	0.000	222	0.030
56	0.075	107	0.016	165	0.000	223	0.047
57	0.035	108	0.047	166	0.022	224	0.062
58	0.090	109	0.171	167	0.024	225	0.038
59	0.075	110	0.105	168	0.000	226	0.072
60	0.037	111	0.063	169	0.000	227	0.000
61	0.000	112	0.105	170	0.000	228	0.069
62	0.024	113	0.456	171	0.005	229	0.004
63	0.064	114	0.188	172	0.096	230	0.086
64	0.132	115	0.079	177	0.347	231	0.005
65	0.255	117	0.389	179	0.066	232	0.061
66	0.300	118	0.195	181	0.000	233	0.026
67	0.027	119	0.116	182	0.318	234	0.044
68	0.026	120	0.158	183	0.160	235	0.088
69	0.080	122	0.223	184	0.076	236	0.101
70	0.090	123	0.195	185	0.159	237	0.024
71	0.068	125	0.362	188	0.010	238	0.493
72	0.530	126	0.844	189	0.024	239	0.000
73	0.202	128	0.606	192	0.000	240	0.182
74	0.069	129	0.580	193	0.009	241	0.000
75	0.194	131	0.762	194	0.013	242	0.397
76	0.510	133	1.732	195	0.000	243	0.100
77	0.456	134	3.319	196	0.034	244	0.195
78	1.354	137	1.211	198	0.047	245	0.500
79	0.412	138	0.749	199	0.001	246	0.063
80	0.295	139	0.450	200	0.003	248	0.070
81	0.747	141	0.066	201	0.113	250	0.031
82	0.007	142	0.576	202	0.000	251	0.143
83	0.088	143	0.465	204	0.174	253	0.036
84	0.369	144	0.408	205	0.000	254	0.035
85	0.872	146	0.439	206	0.000	255	0.054
86	0.933	147	1.126	207	0.000	256	0.008
89	0.615	148	1.181	208	0.031	257	0.000
90	0.865	149	1.108	209	0.049	259	0.019
92	1.118	150	0.504	210	0.005	260	0.040
93	0.802	151	0.290	211	0.046	263	0.345
94	0.288	152	0.262	212	0.104	264	0.222
95	0.138	153	0.414	213	0.127	266	0.038
96	0.086	155	0.605	214	0.071	267	0.000
98	0.035	156	0.699	215	0.071	268	0.000
99	0.219	158	0.103	216	0.059	269	0.047
100	0.065	159	0.055	217	0.070	270	0.163
101	0.014	160	0.012	218	0.080	272	0.312
102	0.273	161	0.000	219	0.063	273	0.609
104	0.001	162	0.000	220	0.085	274	0.513

Table 4.11 Average winter station incident-based congestion index

Station ID	IBCI	Station ID	IBCI	Station ID	IBCI	Station ID	IBCI
54	0.016	105	0.000	163	0.117	221	0.000
55	0.000	106	0.000	164	0.000	222	0.000
56	0.114	107	0.000	165	0.000	223	0.000
57	0.105	108	0.000	166	0.000	224	0.022
58	0.269	109	0.389	167	0.000	225	0.000
59	0.173	110	0.157	168	0.000	226	0.000
60	0.111	111	0.117	169	0.000	227	0.000
61	0.000	112	0.144	170	0.000	228	0.050
62	0.071	113	0.907	171	0.000	229	0.000
63	0.135	114	0.200	172	0.000	230	0.000
64	0.299	115	0.181	177	0.259	231	0.000
65	0.355	117	0.864	179	0.198	232	0.000
66	0.071	118	0.231	181	0.000	233	0.000
67	0.068	119	0.142	182	0.714	234	0.000
68	0.077	120	0.157	183	0.000	235	0.130
69	0.111	122	0.209	184	0.000	236	0.000
70	0.018	123	0.290	185	0.000	237	0.000
71	0.065	125	0.857	188	0.000	238	1.295
72	0.613	126	2.125	189	0.015	239	0.000
73	0.506	128	0.754	192	0.000	240	0.031
74	0.123	129	0.142	193	0.000	241	0.000
75	0.244	131	0.173	194	0.025	242	0.671
76	0.520	133	0.281	195	0.000	243	0.227
77	0.000	134	0.867	196	0.000	244	0.479
78	0.492	137	0.802	198	0.140	245	0.646
79	0.827	138	0.278	199	0.003	246	0.028
80	0.296	139	0.192	200	0.009	248	0.031
81	0.243	141	0.000	201	0.003	250	0.080
82	0.000	142	0.724	202	0.000	251	0.077
83	0.135	143	0.469	204	0.313	253	0.000
84	0.453	144	0.586	205	0.000	254	0.000
85	1.217	146	0.458	206	0.000	255	0.000
86	1.225	147	0.516	207	0.000	256	0.000
89	0.740	148	0.891	208	0.000	257	0.000
90	1.347	149	0.904	209	0.000	259	0.000
92	1.764	150	0.849	210	0.000	260	0.058
93	1.267	151	0.503	211	0.043	263	0.454
94	0.240	152	0.451	212	0.099	264	0.213
95	0.055	153	0.927	213	0.108	266	0.031
96	0.043	155	1.431	214	0.000	267	0.000
98	0.037	156	1.564	215	0.000	268	0.000
99	0.000	158	0.000	216	0.090	269	0.028
100	0.000	159	0.000	217	0.210	270	0.086
101	0.012	160	0.000	218	0.241	272	0.644
102	0.037	161	0.000	219	0.188	273	1.346
104	0.000	162	0.000	220	0.255	274	0.898

Table 4.12 Average spring station incident-based congestion index

Station ID	IBCI	Station ID	IBCI	Station ID	IBCI	Station ID	IBCI
54	0.000	105	0.148	163	0.000	221	0.000
55	0.000	106	0.034	164	0.000	222	0.089
56	0.000	107	0.049	165	0.000	223	0.141
57	0.000	108	0.022	166	0.040	224	0.166
58	0.000	109	0.124	167	0.071	225	0.114
59	0.000	110	0.127	168	0.000	226	0.000
60	0.000	111	0.071	169	0.000	227	0.000
61	0.000	112	0.170	170	0.000	228	0.158
62	0.000	113	0.417	171	0.016	229	0.012
63	0.015	114	0.362	172	0.288	230	0.258
64	0.022	115	0.056	177	0.000	231	0.015
65	0.176	117	0.240	179	0.000	232	0.184
66	0.454	118	0.320	181	0.000	233	0.028
67	0.012	119	0.099	182	0.000	234	0.000
68	0.000	120	0.133	183	0.000	235	0.000
69	0.000	122	0.278	184	0.025	236	0.133
70	0.000	123	0.204	185	0.158	237	0.071
71	0.000	125	0.052	188	0.003	238	0.185
72	0.723	126	0.102	189	0.000	239	0.000
73	0.102	128	0.405	192	0.000	240	0.235
74	0.083	129	0.338	193	0.026	241	0.000
75	0.120	131	0.607	194	0.015	242	0.343
76	0.006	133	1.850	195	0.000	243	0.000
77	0.000	134	3.130	196	0.046	244	0.000
78	0.173	137	0.942	198	0.000	245	0.000
79	0.223	138	0.544	199	0.000	246	0.000
80	0.294	139	0.395	200	0.000	248	0.000
81	0.306	141	0.000	201	0.000	250	0.012
82	0.000	142	1.003	202	0.000	251	0.353
83	0.130	143	0.831	204	0.163	253	0.108
84	0.019	144	0.636	205	0.000	254	0.105
85	0.272	146	0.661	206	0.000	255	0.161
86	0.435	147	0.627	207	0.000	256	0.000
89	0.416	148	0.037	208	0.093	257	0.000
90	0.381	149	0.108	209	0.147	259	0.056
92	0.550	150	0.191	210	0.015	260	0.062
93	0.526	151	0.253	211	0.096	263	0.457
94	0.121	152	0.309	212	0.214	264	0.285
95	0.080	153	0.314	213	0.272	266	0.000
96	0.090	155	0.385	214	0.056	267	0.000
98	0.000	156	0.527	215	0.095	268	0.000
99	0.068	158	0.310	216	0.086	269	0.000
100	0.068	159	0.124	217	0.000	270	0.000
101	0.031	160	0.000	218	0.000	272	0.000
102	0.205	161	0.000	219	0.000	273	0.043
104	0.003	162	0.000	220	0.000	274	0.559

Table 4.13 Average summer station incident-based congestion index

Station ID	IBCI	Station ID	IBCI	Station ID	IBCI	Station ID	IBCI
54	0.053	105	0.000	163	0.031	221	0.000
55	0.108	106	0.000	164	0.000	222	0.000
56	0.111	107	0.000	165	0.000	223	0.000
57	0.000	108	0.121	166	0.025	224	0.000
58	0.000	109	0.000	167	0.000	225	0.000
59	0.052	110	0.031	168	0.000	226	0.216
60	0.000	111	0.000	169	0.000	227	0.000
61	0.000	112	0.000	170	0.000	228	0.000
62	0.000	113	0.043	171	0.000	229	0.000
63	0.040	114	0.003	172	0.000	230	0.000
64	0.074	115	0.000	177	0.783	231	0.000
65	0.235	117	0.062	179	0.000	232	0.000
66	0.374	118	0.034	181	0.000	233	0.049
67	0.000	119	0.108	182	0.238	234	0.133
68	0.000	120	0.182	183	0.479	235	0.133
69	0.129	122	0.182	184	0.203	236	0.170
70	0.252	123	0.090	185	0.320	237	0.000
71	0.138	125	0.176	188	0.028	238	0.000
72	0.255	126	0.306	189	0.056	239	0.000
73	0.000	128	0.657	192	0.000	240	0.281
74	0.000	129	1.262	193	0.000	241	0.000
75	0.219	131	1.506	194	0.000	242	0.176
76	1.002	133	3.066	195	0.000	243	0.074
77	1.368	134	5.959	196	0.056	244	0.104
78	3.398	137	1.887	198	0.000	245	0.853
79	0.186	138	1.425	199	0.000	246	0.163
80	0.294	139	0.764	200	0.000	248	0.178
81	1.691	141	0.199	201	0.337	250	0.000
82	0.020	142	0.000	202	0.000	251	0.000
83	0.000	143	0.096	204	0.046	253	0.000
84	0.636	144	0.000	205	0.000	254	0.000
85	1.126	146	0.197	206	0.000	255	0.000
86	1.140	147	2.237	207	0.000	256	0.025
89	0.690	148	2.617	208	0.000	257	0.000
90	0.866	149	2.312	209	0.000	259	0.000
92	1.041	150	0.473	210	0.000	260	0.000
93	0.614	151	0.114	211	0.000	263	0.123
94	0.502	152	0.025	212	0.000	264	0.169
95	0.280	153	0.000	213	0.000	266	0.083
96	0.126	155	0.000	214	0.157	267	0.000
98	0.068	156	0.006	215	0.118	268	0.000
99	0.588	158	0.000	216	0.000	269	0.115
100	0.127	159	0.040	217	0.000	270	0.402
101	0.000	160	0.037	218	0.000	272	0.293
102	0.578	161	0.000	219	0.000	273	0.439
104	0.000	162	0.000	220	0.000	274	0.083

Table 4.14 Incident-based congestion index for the different months and segments

Segment #	Dec-96	Jan-97	Feb-97	Mar-97	Apr-97	May-97	Jun-97	Jul-97	Aug-97	Avg. segment
1	0.215	0.088	0.309	0.080	0.002	0.199	0.167	0.437	0.431	0.214
2	1.492	0.104	0.719	0.058	0.131	0.634	1.164	0.422	0.329	0.561
3	0.000	0.011	0.015	0.087	0.005	0.097	0.264	0.064	0.116	0.073
4	0.337	0.410	0.173	0.267	0.037	0.296	0.165	0.005	0.000	0.188
5	1.114	0.155	0.497	0.894	0.937	0.451	2.562	2.120	0.011	0.971
6	0.297	0.193	0.623	0.313	0.317	0.092	0.265	0.535	0.079	0.302
7	0.274	0.008	0.073	0.000	0.000	0.056	0.493	0.059	0.079	0.116
8	0.066	0.044	0.037	0.045	0.019	0.011	0.014	0.017	0.101	0.039
9	0.039	0.000	0.141	0.000	0.063	0.163	0.000	0.000	0.039	0.049
10	0.286	0.205	0.038	0.036	0.134	0.073	0.116	0.154	0.058	0.122
11	0.000	0.059	0.016	0.163	0.071	0.000	0.096	0.003	0.000	0.045
12	0.379	0.585	0.146	0.164	0.206	0.033	0.327	0.026	0.159	0.225
Avg. month	0.329	0.379	0.168	0.153	0.166	0.264	0.149	0.333	0.136	0.230

incident-based congestion. On this segment, station 79 had the highest index value of 0.827, which translates to 9.0 minutes of average daily incident-based congestion. Segment 2 experienced very high index values. Station 92 had the highest index value of 1.764, which is equivalent to 19.1 minutes of average daily incident-based congestion. Segment 3 did not show any noticeable congestion.

In the spring, there was an over all reduction in incident-based congestion. Segment 1 had very low values of incident-based congestion compared to segments 2 and 3. Station 72 had the highest index value of 0.723. This value translates to 7.8 minutes of average daily incident-based congestion. On segment 2, station 92 had the highest index value of 0.550. This value corresponds to 5.9 minutes of average daily incident-based congestion. On segment 3, station 102 had the highest index value of 0.205. This value is equivalent to 2.2 minutes of average daily incident based congestion.

The pattern in the summer shows an increase in incident-based congestion on all segments. Station 78 on segment 1 had the highest index value of 3.398. This value translates to 36.7 minutes of average daily incident-based congestion. Segment 2 had higher index values than the winter. On segment 2, station 86 had the highest index value of 1.14. This value is equivalent to 12.3 minutes of average daily incident based congestion. On segment 3, station 99 had the highest value of 0.588. This value corresponds to 6.4 minutes of average daily incident-based congestion.

The average of the three seasons is plotted in Figure 4.2 (d). This figure shows station 78 on segment 1 with an index values of 1.354. This value is equivalent to 16.6 minutes of daily incident-based congestion. On segment 2, station 92 had the highest index value of 1.118, which translates to 12.1 minutes of daily incident-based congestion.

On segment 3, station 102 had the highest index value of 0.273, which corresponds to 2.9 minutes of daily incident-based congestion.

4.3.1.2 Station Incident-based Congestion Index on EB I-94

The seasonal variation in the incident-based congestion index for segments 4, 5, and 6 on EB I-94 is illustrated in Figure 4.3. The majority of the stations on this direction of the freeway show incident-based congestion indices below 1.00. In the winter, station 113 on segment 4 demonstrated the highest index value of 0.907, which translates to 9.8 minutes of average daily incident-based congestion. On segment 5, station 126 had the highest index value of 2.125, which corresponds to 23.0 minutes of average daily incident-based congestion. Almost half the stations on segment 6 show no incident-based congestion. On segment 6, station 156 had the highest index value of 1.564, which translates to 16.9 minutes of average daily incident-based congestion.

In the spring, the incident-based congestion on all segments was slightly lower than in the winter. On segment 4, Station 113 shows the highest index value among the stations on this segment. Its index value was 0.417, which translates to 4.5 minutes of average daily incident-based congestion. Segment 5 shows almost the same amount of congestion compared to the winter, where station 134 had the highest value of 3.130. This value corresponds to 33.8 minutes of average daily incident based congestion. Segment 6 also had a slight decrease in the incident-based congestion index compared to the winter. On this segment, station 142 had the highest index value of 1.003. This value translates to 10.8 minutes of average daily incident based congestion.

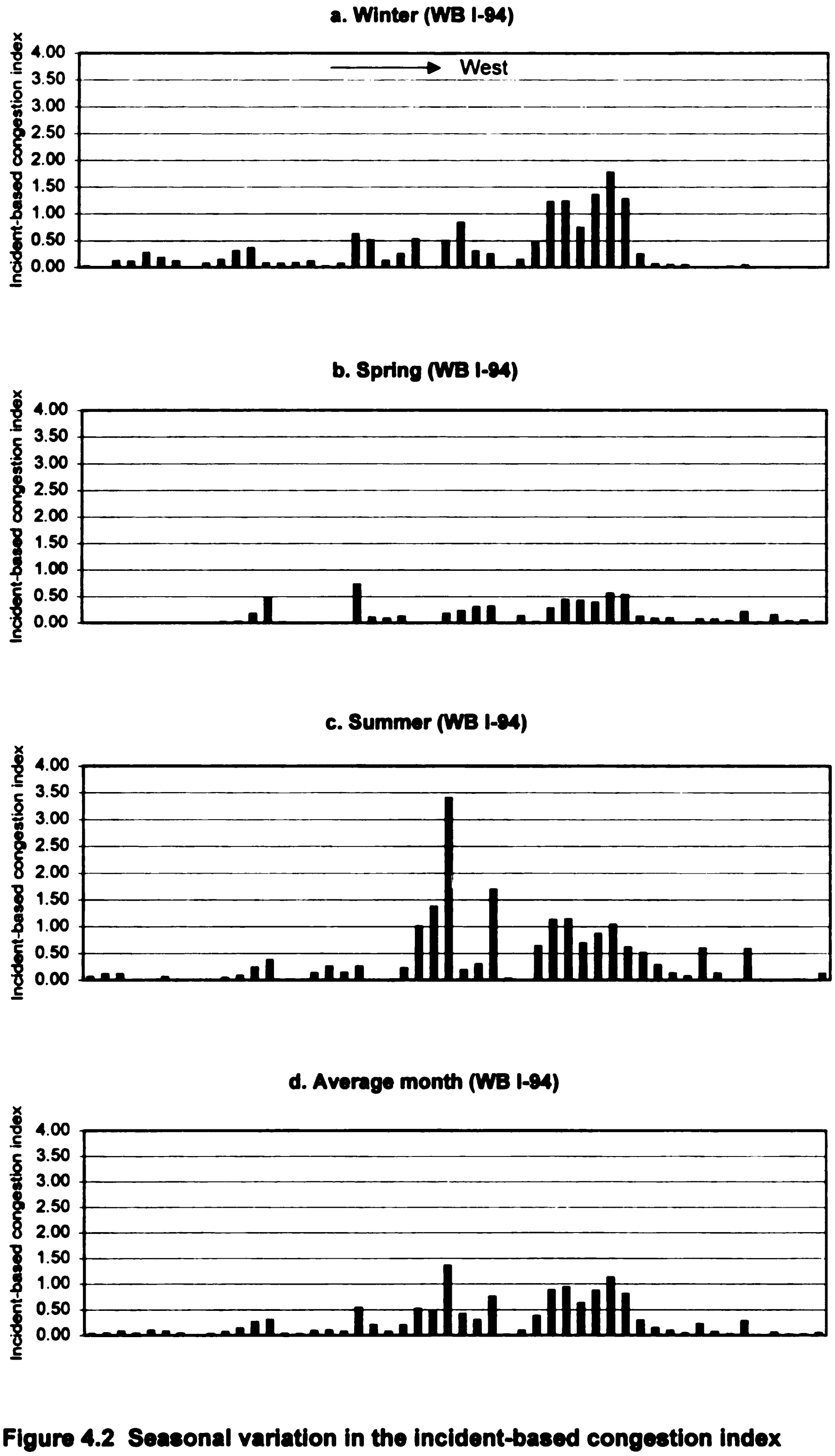


Figure 4.2 Seasonal variation in the incident-based congestion index on WB I-94

The pattern in the summer exhibited a similar pattern as the spring, where segment 4 experienced almost no incident-based congestion compared to the winter and spring. Stations 120 and 122 on this segment show the highest index value among the stations on this segment. Their index value was 0.182, which translates to 2.0 minutes of average daily incident-based congestion. On segment 5, station 134 maintained its high value among the rest of the segment's stations. Its index value was 5.959. This value translates to 64.4 minutes of average daily incident-based congestion. On segment 6, stations 147, 148, and 149 had the highest index values of 2.237, 2.617, and 2.312 which translates to 24.2, 28.3, and 25.0 minutes of average daily incident-based congestion respectively. The rest of the stations on this segment show almost no incident-based congestion.

Figure 4.3 (d) illustrates the season's average in the incident-based congestion index. On segment 4, station 113 showed a high index value of 0.456, which translates to 4.9 minutes of daily incident-based congestion. On segment 5, station 134 had the highest index value of 3.319, which is 35.8 minutes of daily incident-based congestion. On Segment 6, station 147 had the highest index value of 1.126, which is 12.2 minutes of daily incident-based congestion.

4.3.1.3 Station Incident-based Congestion Index on NB M-10

Figure 4.4 shows the seasonal variation in the incident-based congestion index for segments 7, 8, and 9 on NB M-10. In the winter, most of the stations on segment 7 had very low incident-based congestion. Station 182 had the highest index value of 0.714, which translates to 7.7 minutes of average daily incident-based congestion. Segment 8

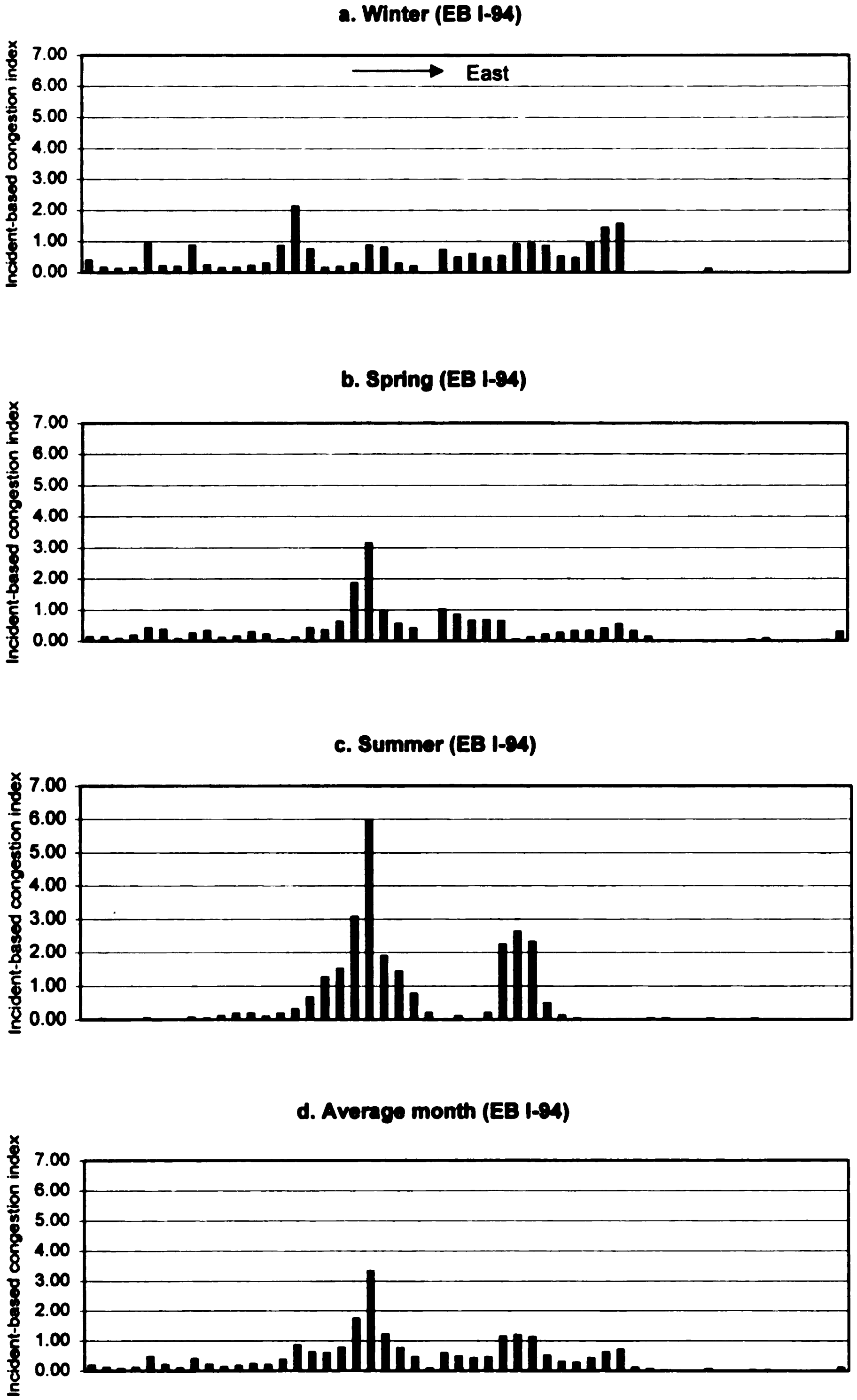


Figure 4.3 Seasonal variation in the incident-based congestion index on EB I-94

experienced the lowest index values with station 198 showing the highest value among the segment stations. This station had an index value of 0.14, which translates to 1.5 minutes of average daily incident-based congestion. The stations on segment 9 showed higher index values compared to segments 7 and 8, and of those stations, station 220 had the highest index value of 0.255, which corresponds to 2.8 minutes of average daily incident-based congestion.

In the spring, segment 7 showed almost no incident-based congestion. Station 185 shows the highest index value of 0.158 that translates to 1.7 minutes of average daily incident-based congestion. Segment 8 also showed no congestion except for station 204, which had an index value of 0.163. This translates to 1.8 minutes of daily incident-based congestion. Segment 9 showed higher value of the incident-based congestion; station 213 had the highest value of 0.272. This value translates to 2.9 minutes of average daily incident based congestion.

The pattern in the summer exhibited slightly higher index values for some stations compared to the winter and spring. Station 177 on segment 7 showed the highest index value compared to the rest of the segment's stations. Its index value was 0.783, which translates to 8.5 minutes of average daily incident-based congestion. Segment 8 also showed low index values. On segment 8, station 201 had the highest index value among the rest of the segment's stations. Its index value was 0.337, which translates to 3.6 minutes of average daily incident-based congestion. Segment 9 also showed very low congestion. On this segment, station 214 had the highest index value of 0.157, which translates to 1.7 minutes of average daily incident-based congestion.

Part "d" of Figure 4.4 illustrates the average of the three seasons. This figure shows that on segment 7, station 177 had the highest index value of 0.347, which translates to 3.7 minutes of daily incident-based congestion. On segment 8, station 204 had the highest index value of 0.174, which corresponds to 1.9 minutes of daily incident-based congestion. On Segment 9, station 213 had the highest index value of 0.127, which is equivalent to 1.4 minutes of daily incident-based congestion.

4.3.1.4 Station Incident-based Congestion Index on SB M-10

The seasonal variation in the incident-based congestion index for segments 10, 11, and 12 on SB M-10 is illustrated in Figure 4.5. In the winter, most of the stations on segment 10 had very low incident-based congestion. Station 238 had the highest value of 1.295, which is equivalent to 14.0 minutes of average daily incident-based congestion. Segment 11 experienced no incident-based congestion, while Segment 12 shows no incident-based congestion except for a few stations. On this segment, station 273 had the highest index value of 1.346, which is equal to 14.5 minutes of average daily incident-based congestion.

In the spring, the incident-based congestion on most of the stations was below 0.4 with the exception of few stations. The station with the highest index value on segment 10 was station 242, which had an index value of 0.343. This corresponds to 3.7 minutes of average daily incident-based congestion. Segment 11 also showed low incident-based congestion where station 251 had an index value of 0.353, which translates to 3.8 minutes of daily incident-based congestion. Segment 12 shows low incident-based congestion.

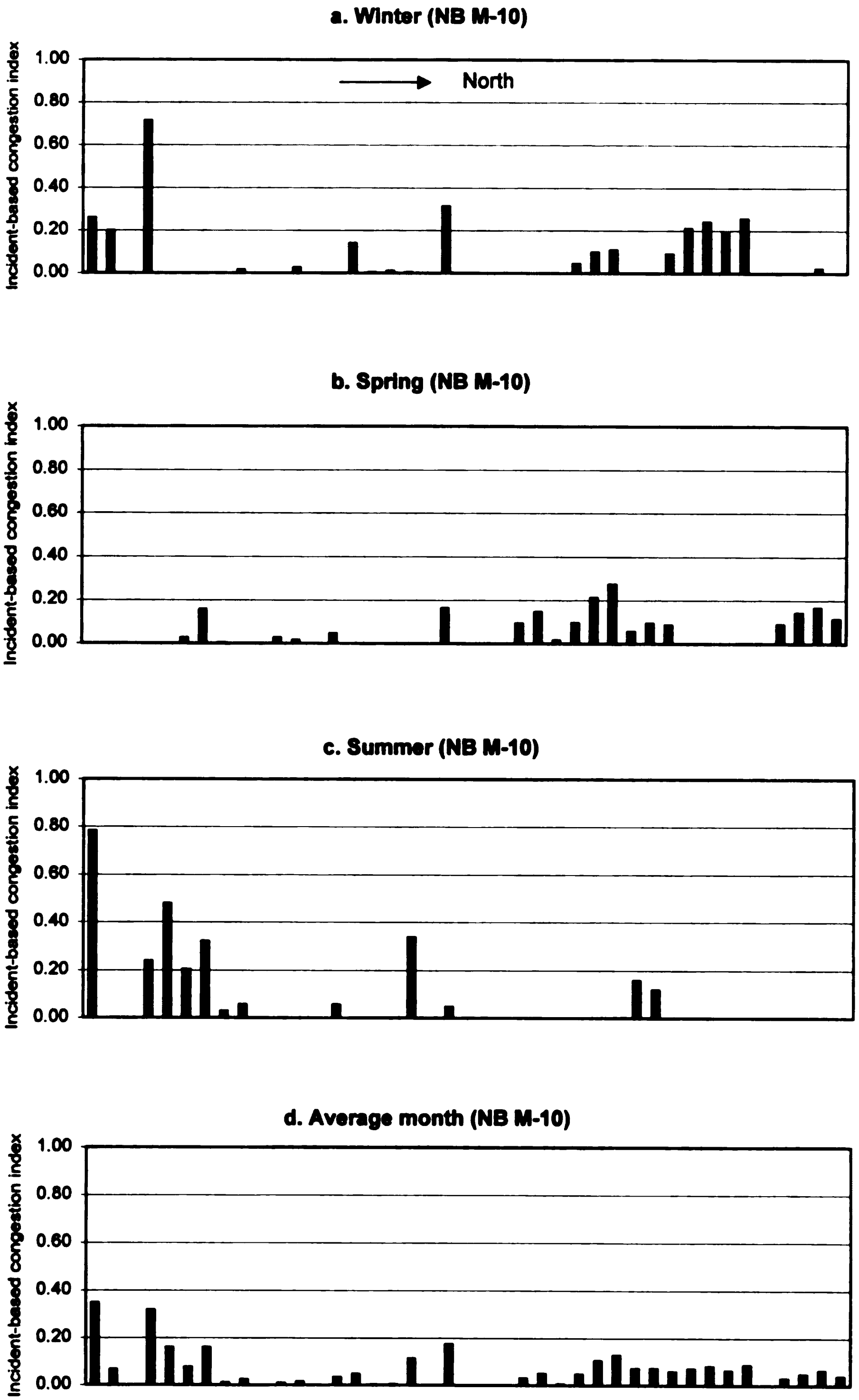


Figure 4.4 Seasonal variation in the incident-based congestion index on NB M10

The station with the highest index value on this segment was 274, with an index value of 0.559, which is equivalent to 6.0 minutes of average daily incident-based congestion.

The pattern in the summer showed lower index values compared to the winter and slightly higher than the spring. Station 245 on segment 10 showed the highest index value compared to the rest of the segment's stations. Its index value was 0.853, which translates to 9.2 minutes of average daily incident-based congestion. Segment 11 showed no incident based congestion, and segment 12 showed very low incident-based congestion. On this segment, station 273 had the highest index value of 0.439. This value is equivalent to 4.7 minutes of average daily incident-based congestion.

Figure 4.5 "d" shows a plot of the average of the three seasons. On segment 10, station 245 showed the highest index values of 0.50, which translates to 5.4 minutes of daily incident-based congestion. On segment 11, station 251 had the highest index value of 0.143, which corresponds to 1.5 minutes of daily incident-based congestion. On Segment 12, station 273 had the highest index value of 0.609, which is equivalent to 6.6 minutes of daily incident-based congestion. The analysis shows that M-10 had considerably lower incident-based congestion than I-94.

4.3.2 Segment Monthly Variation of the Incident-based Congestion Index

Figure 4.6 illustrates the monthly variation in the incident-based congestion index on westbound I-94, which includes segments 1, 2, and 3. During the winter, segment 2 had higher values of incident-based congestion than segments 1 and 3, especially for the month of December where the index value was strikingly high. Segment 3 shows the lowest values for all months except for the months of March and June. During the spring,

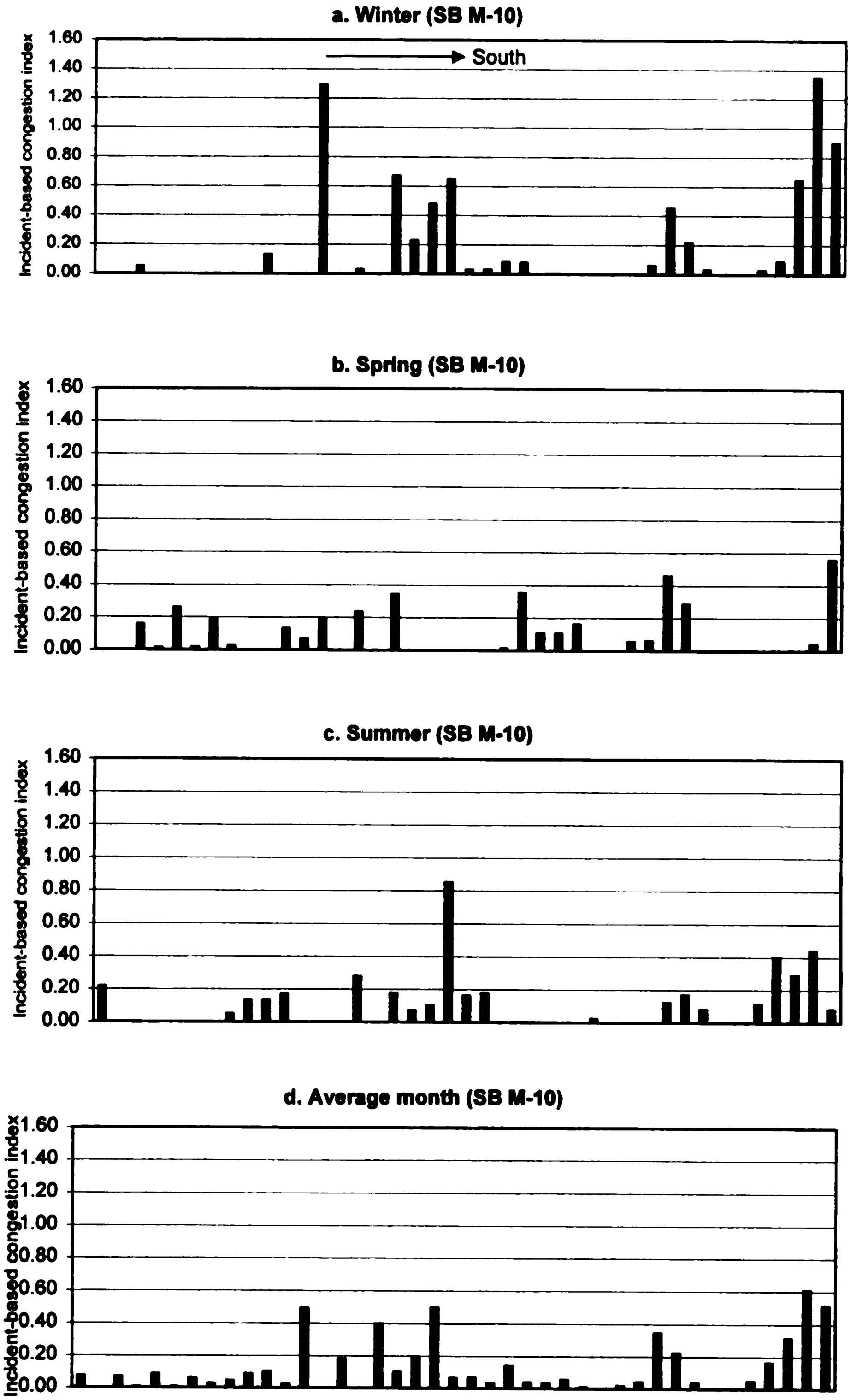


Figure 4.5 Seasonal variation in the incident-based congestion index on SB M10

segment 2 had a higher index value than the other two segments except for the month of March where segments 1 and 3 show higher index values. In the summer, the congestion index was relatively high on segment 2 during the month of June. On the average, segments 1, 2, and 3 had index values of 0.214, 0.561, and 0.073. These values translate to 2.3, 6.1, and 0.8 minutes of incident-based congestion per day per station on segments 1, 2, and 3, respectively.

Figure 4.7 illustrates the monthly variation in the incident-based congestion index on eastbound I-94, which includes segments 4, 5, and 6. Segment 5 shows a noticeably higher index value than the other two segments. On the average, segments 4, 5, and 6 had index values of 0.188, 0.971, and 0.302. These values translate to 2.0, 10.5, and 3.3 minutes of daily incident-based congestion per station for segments 4, 5, and 6, respectively.

Figure 4.8 illustrates the monthly variation of the incident-based congestion index on northbound M-10, which includes segments 7, 8, and 9. These segments had relatively low values. There is very little incident-based congestion on these segments compared to I-94. On the average, segments 7, 8, and 9 had index values of 0.116, 0.039, and 0.049. These values translate to 1.3, 0.4, and 0.5 minutes of incident-based congestion per day per station for segments 7, 8, and 9, respectively.

Figure 4.9 illustrates the monthly variation of the incident-based congestion index on southbound M-10, which includes segments 10, 11, and 12. On the average, segments 10, 11, and 12 had index values of 0.122, 0.045, and 0.225. These values translate to 1.3, 0.5, and 2.4 minutes of incident-based congestion per day per station for segments 10, 11,

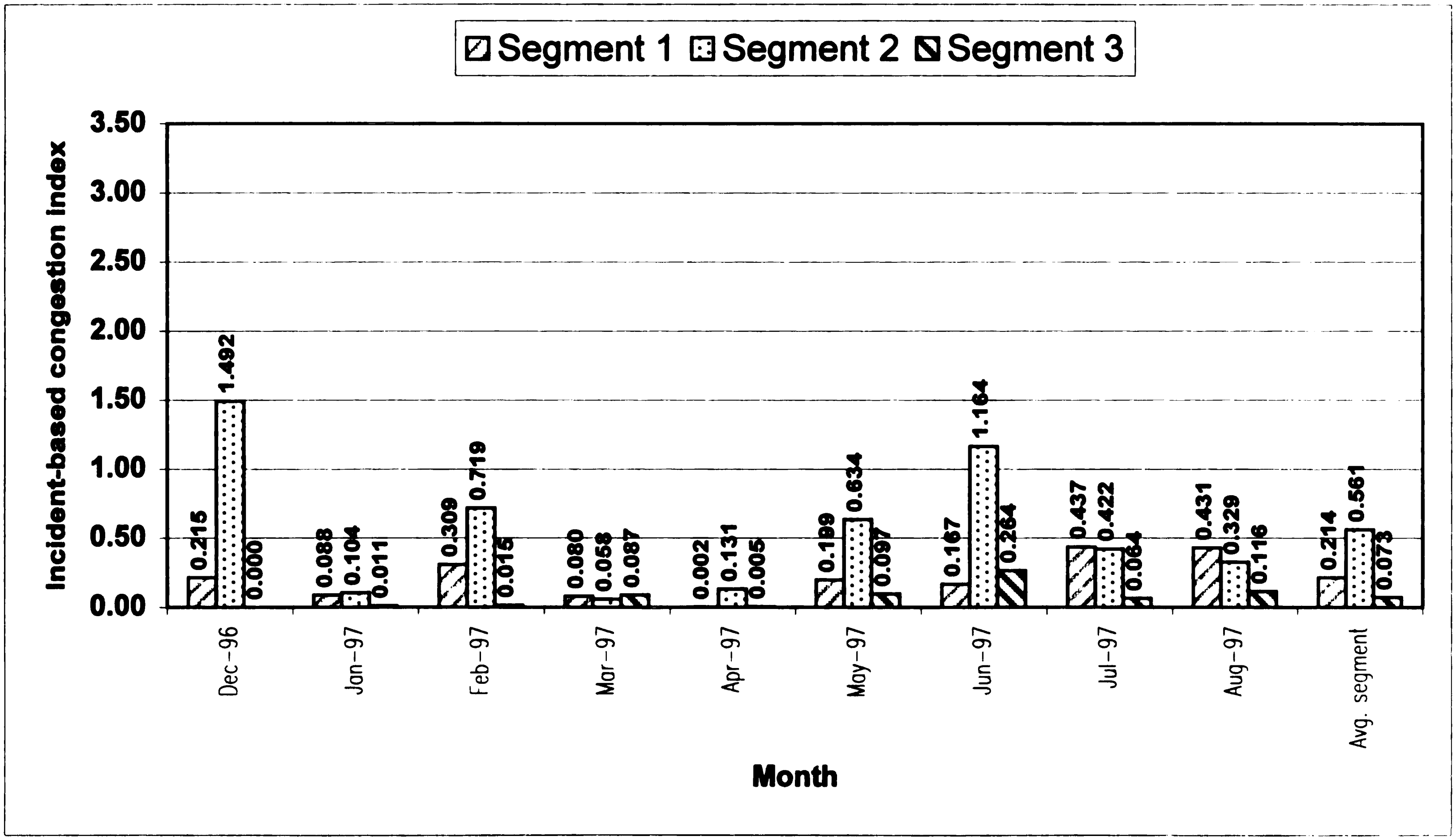


Figure 4.6 Monthly variation of the incident-based congestion index for segments 1, 2, and 3 on WB I-94

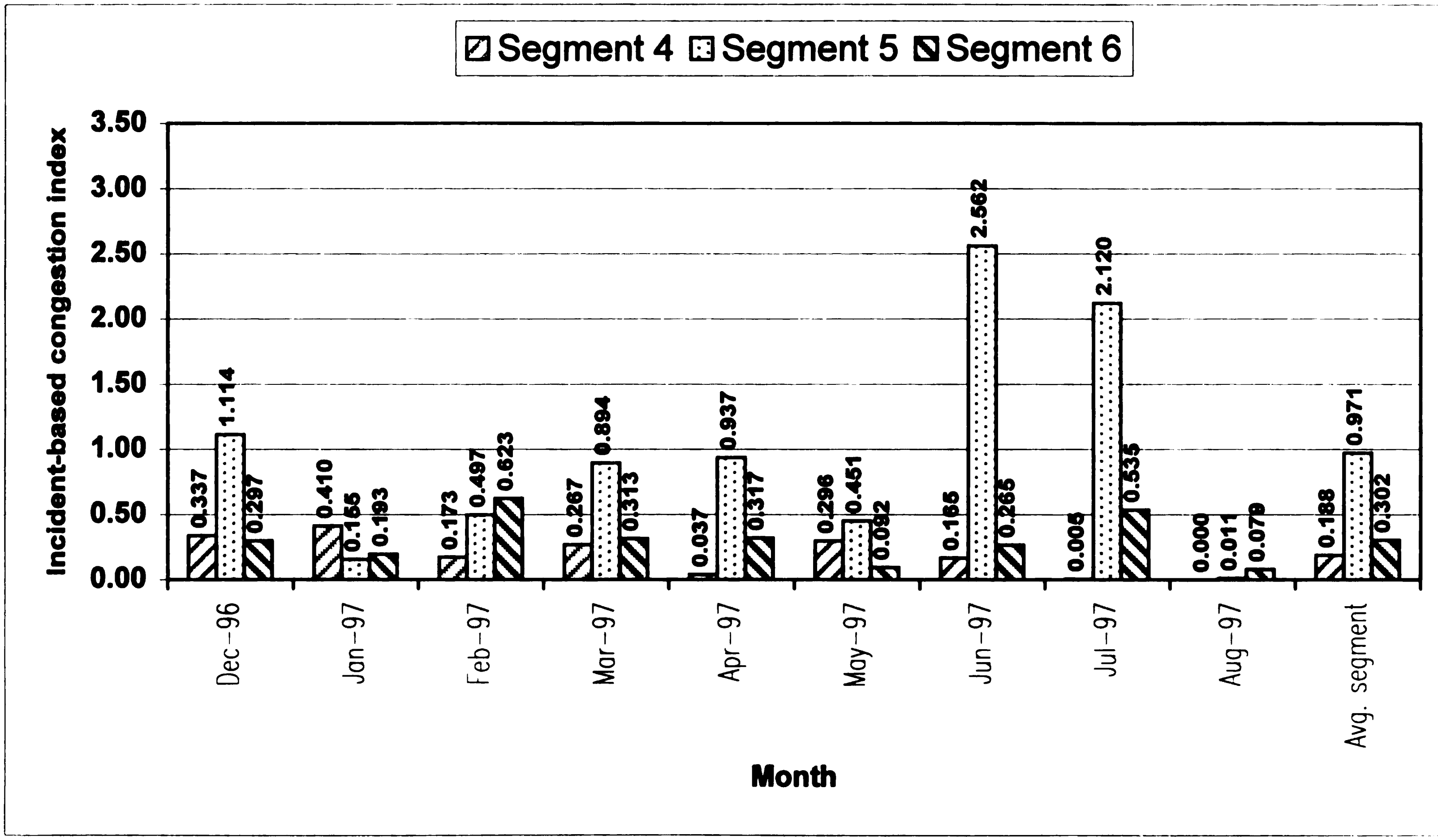


Figure 4.7 Monthly variation of the incident-based congestion index for segments 4, 5, and 6 on EB I-94

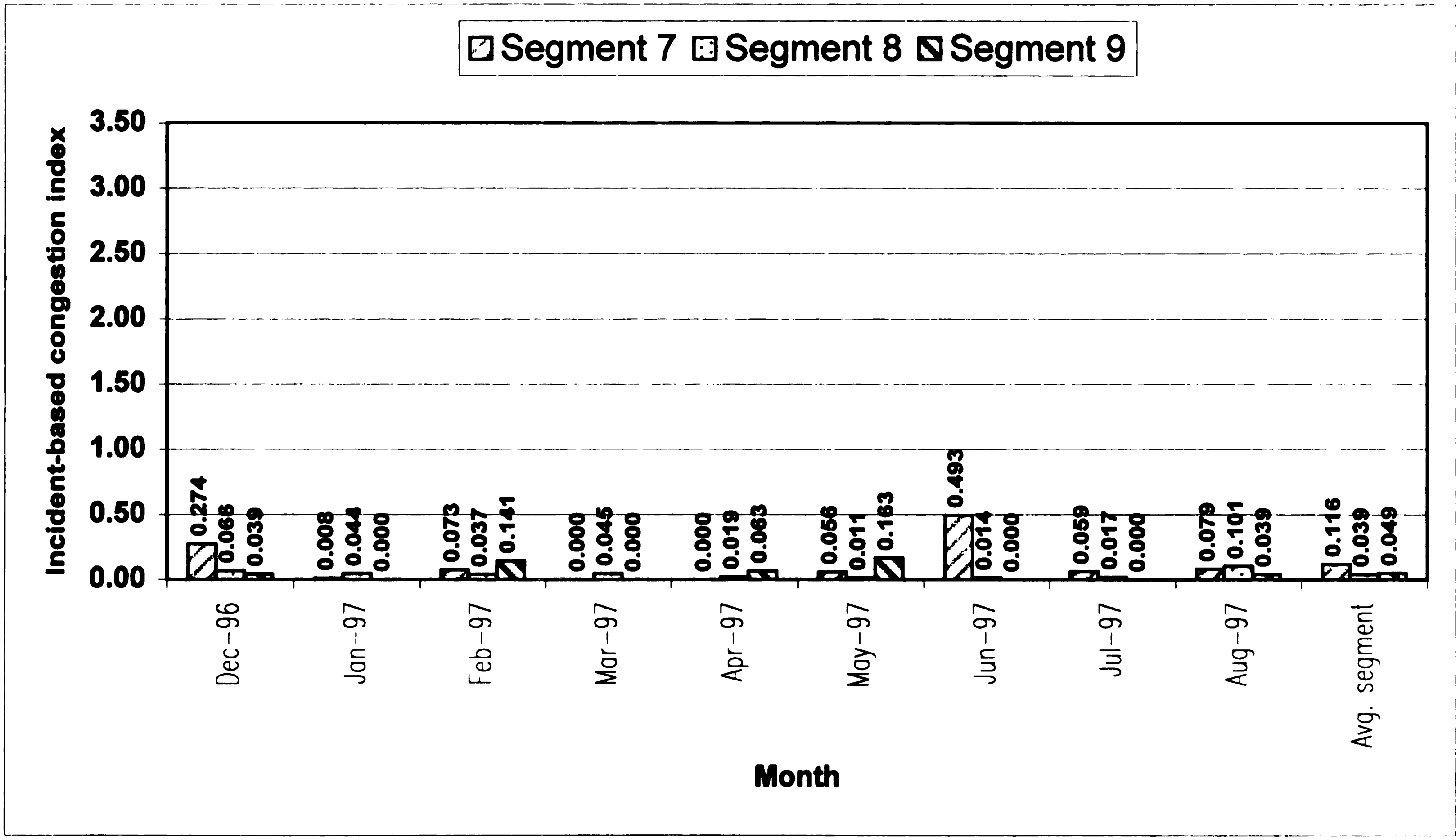


Figure 4.8 Monthly variation of the incident-based congestion index for segments 7, 8, and 9 on NB M-10

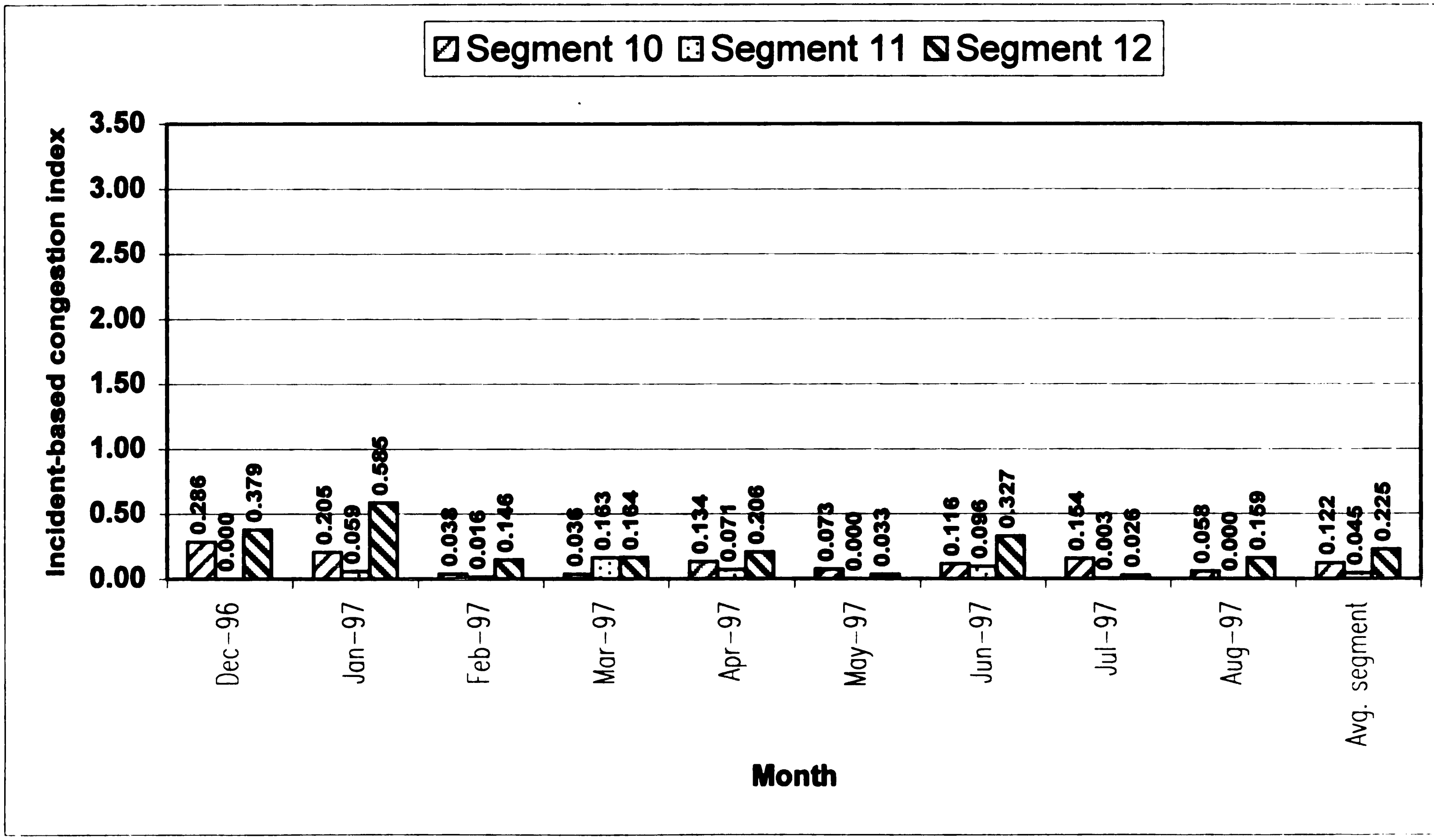


Figure 4.9 Monthly variation of the incident-based congestion index for segments 10, 11, and 12 on SB M-10

and 12, respectively. These values are somewhat higher than the values for northbound M-10, but still significantly less than the values for I-94.

4.3.3 Segment Variation of the Incident-based Congestion Index

In order to isolate locations with high incident-based congestion, the nine sets of data were used to estimate the incident-based congestion index for the different segments. Figure 4.10 illustrates the variation in the incident-based congestion index among the different segments.

On I-94, the eastbound shows about 1.6 times the westbound incident-based congestion when aggregated by direction. The incident-based congestion index and number of daily minutes of incident-based congestion per station were 0.262 and 2.8 minutes for westbound I-94 and 0.415 and 4.5 minutes for eastbound I-94. Segments 2 and 5, which are located in the area that includes interchanges with I-96 and M-10 experienced higher levels of incident-based congestion than the other segments.

On M-10, the southbound segments show a higher level of incident-based congestion than the northbound segments, although both directions are relatively incident free compared to I-94. The incident-based congestion index and number of daily minutes of incident-based congestion per station were 0.063 and 0.7 minute for the northbound segments and 0.127 and 1.4 minutes for the southbound segments. Segment 12 had the highest index value on M-10.

The aggregate incident-based congestion index and number of daily minutes of incident-based congestion per station were 0.34 and 3.7 minutes for I-94 and 0.95 and 1.0 minutes for M-10. The network wide incident-based congestion index and number of

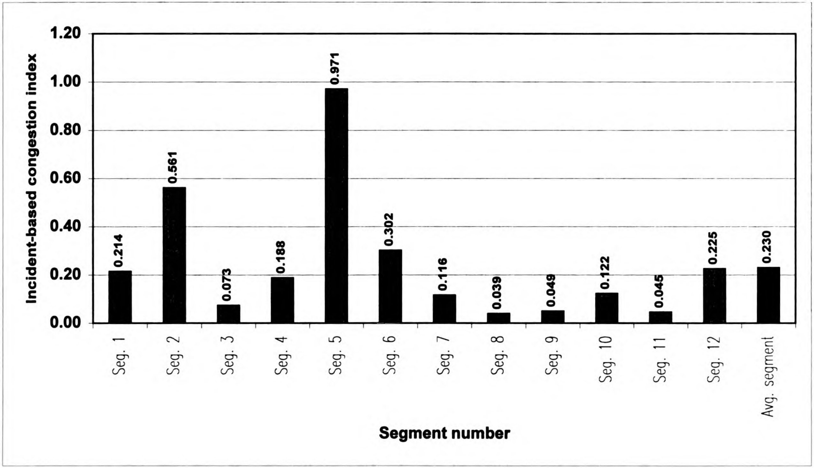


Figure 4.10 Segment variation of the incident-based congestion index

daily minutes of incident-based congestion per station were 0.230 and 2.5 minutes respectively. Table 4.15 shows the values of the incident-based congestion index and number of daily minutes of congestion per station for the different directions of the freeways.

Table 4.15 Incident-based congestion index and number of daily minutes of congestion per station for the different directions of the freeways.

Freeway	Incident-based congestion index	Number of daily minutes of incident-based congestion per station
WB I-94 (Segments 1, 2, and 3)	0.262	2.8
EB I-94 (Segments 4, 5, and 6)	0.415	4.5
NB M-10 (Segments 7, 8, and 9)	0.063	0.7
SB M-10 (Segments 10, 11, and 12)	0.127	1.4
I-94	0.340	3.7
M-10	0.095	1.0
I-94 and M-10	0.230	2.5

4.3.4 System Monthly Variation of the Incident-based Congestion Index

In this subsection, the values of incident-based congestion for the different months are compared. The average value of incident-based congestion for the whole system is 0.230 as shown in Table 4.15. This value translates to 2.5 minutes of daily incident-based congestion for any given station in the network. The month of January 1997 has the highest index value of 0.379, and this value translates to 4.1 minutes of daily incident-based congestion at any given station in the network during that month. The month of August 1997 shows the lowest index value of 0.136 and that is equivalent to 1.5 minutes of daily incident-based congestion for any given station in the network. Figure 4.11 illustrates the monthly variation of the incident-based congestion index.

4.4 Incident Frequency and Queue Length

This section presents the results of the incident frequency by length obtained by processing the nine sets of traffic data described in section 4.2. It includes the results of time-based variation in incident frequency, segment variation in incident frequency, system-based variation in incident frequency, and incident queue length. Table 4.16 shows the incident frequency and queue length for the different months.

The distribution of incident frequency and queue length by month is illustrated in Figures 4.12, 4.13, and 4.14. The month of December shows the highest frequencies and April and August have the lowest. In all months the majority of incidents affected only one station.

The frequency of incidents with various lengths that occurred on each of the network segments is illustrated in Figure 4.15. Segments 5 and 6 had high rates of 9 incidents per mile per month, while segments 9 and 11 had low rates of 1 incident per mile per month and the rest of the segments ranged from 3 to 7 incidents per mile per month.

The variation in incident frequency per mile that occurred on the network for each month is illustrated in Figure 4.16. This figure shows the network monthly variation of incident frequency per mile. In the average month, there were 171 incidents of various lengths on the network. During the winter and summer, the incident frequency tends to be higher than in the spring.

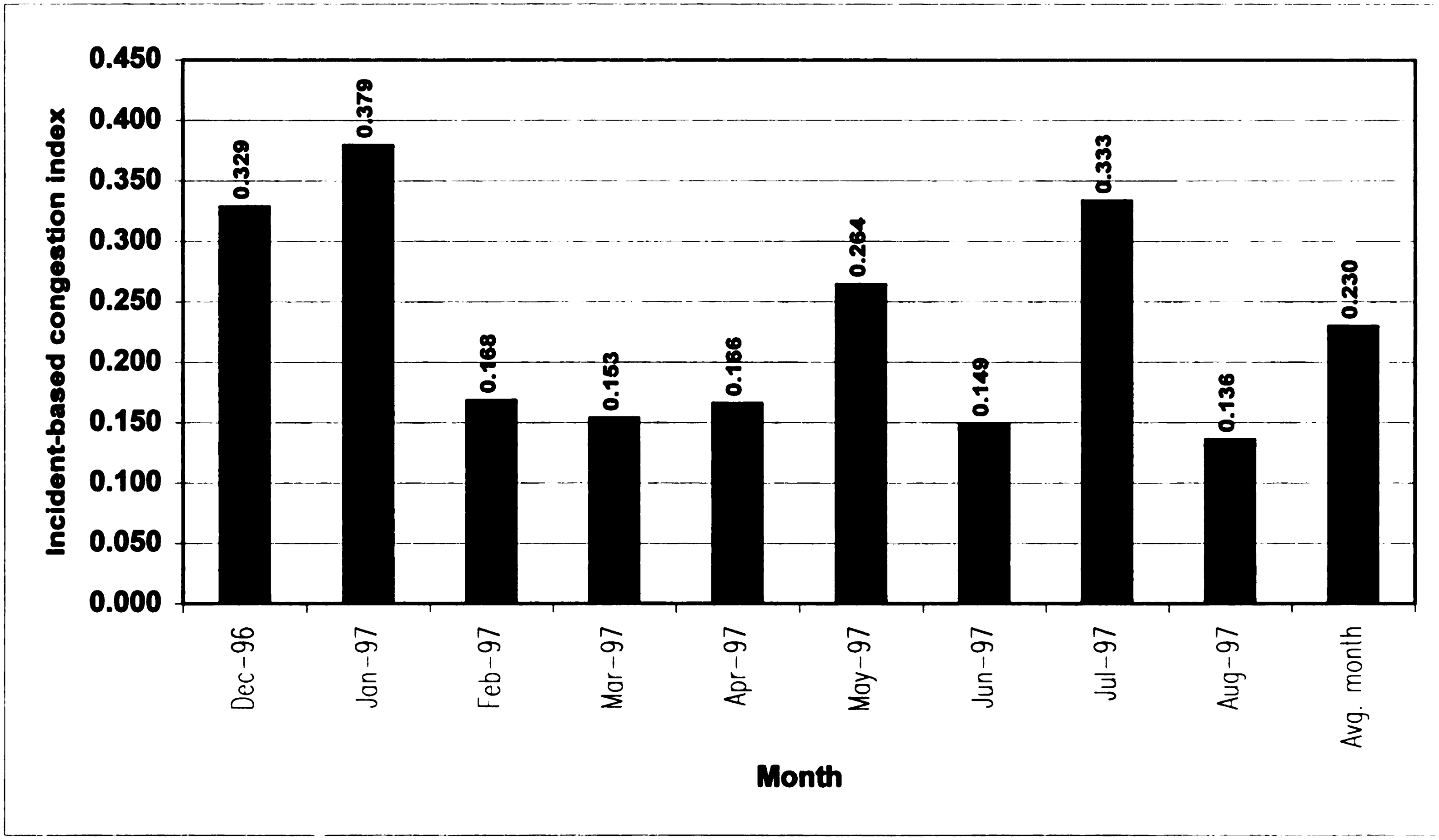


Figure 4.11 Monthly variation of the system-wide incident-based congestion index

Table 4.16 Incident frequency and queue length for the different months

Month	Incident frequency and queue length (miles)								System-wide Incident frequency per mile
	L	0.0 to 0.5 + L	0.5 to 1.0 + L	1.0 to 1.5 + L	1.5 to 2.0 + L	2.0 to 2.5 + L	2.5 to 3.0 + L	> 3.0 + L	
Dec-96	192	46	20	15	7	0	0	0	7
Jan-97	151	35	9	2	5	2	0	0	5
Feb-97	81	35	20	9	4	2	0	0	4
Mar-97	92	43	9	4	5	0	0	0	4
Apr-97	86	37	15	4	2	0	0	0	3
May-97	104	27	11	7	0	2	0	0	4
Jun-97	156	48	23	16	4	2	0	0	6
Jul-97	91	33	31	21	0	0	0	0	4
Aug-97	86	15	11	8	0	2	0	0	3
Avg. month	115	35	17	10	3	1	0	0	4

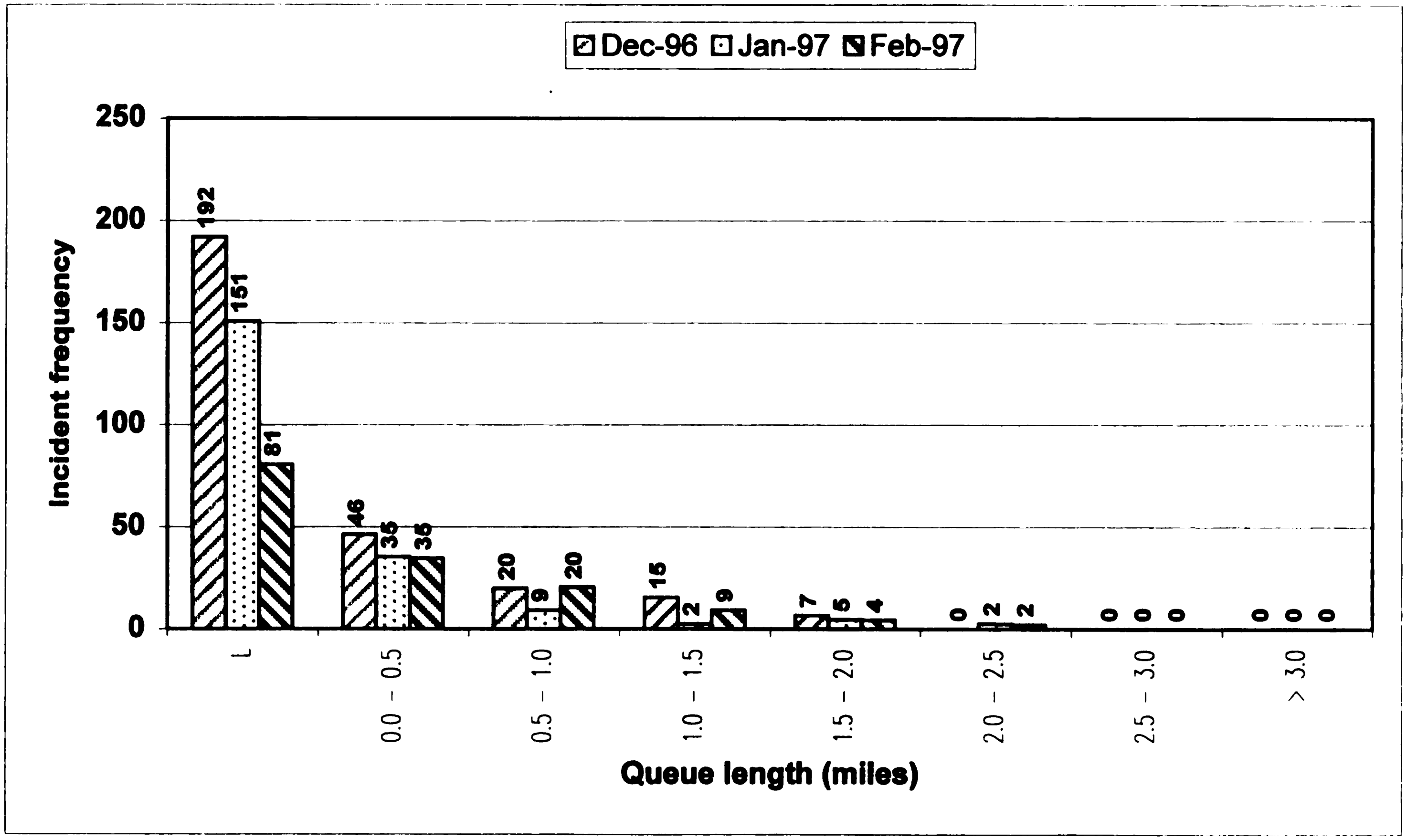


Figure 4.12 System-wide incident frequency by queue length for the months of Dec-96, Jan-97, and Feb-97

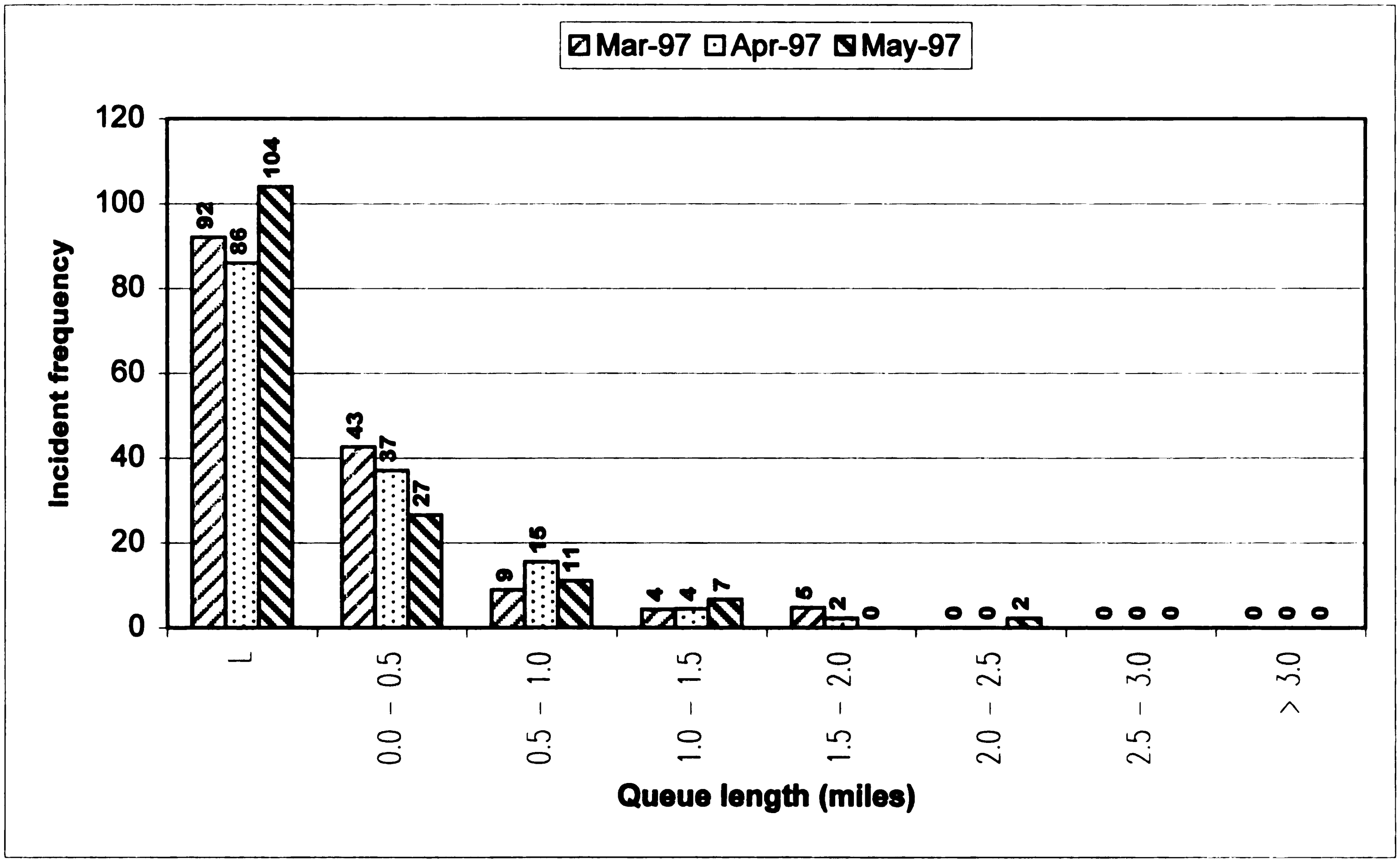


Figure 4.13 System-wide incident frequency by queue length for the months of Mar-97, Apr-97, and May-97

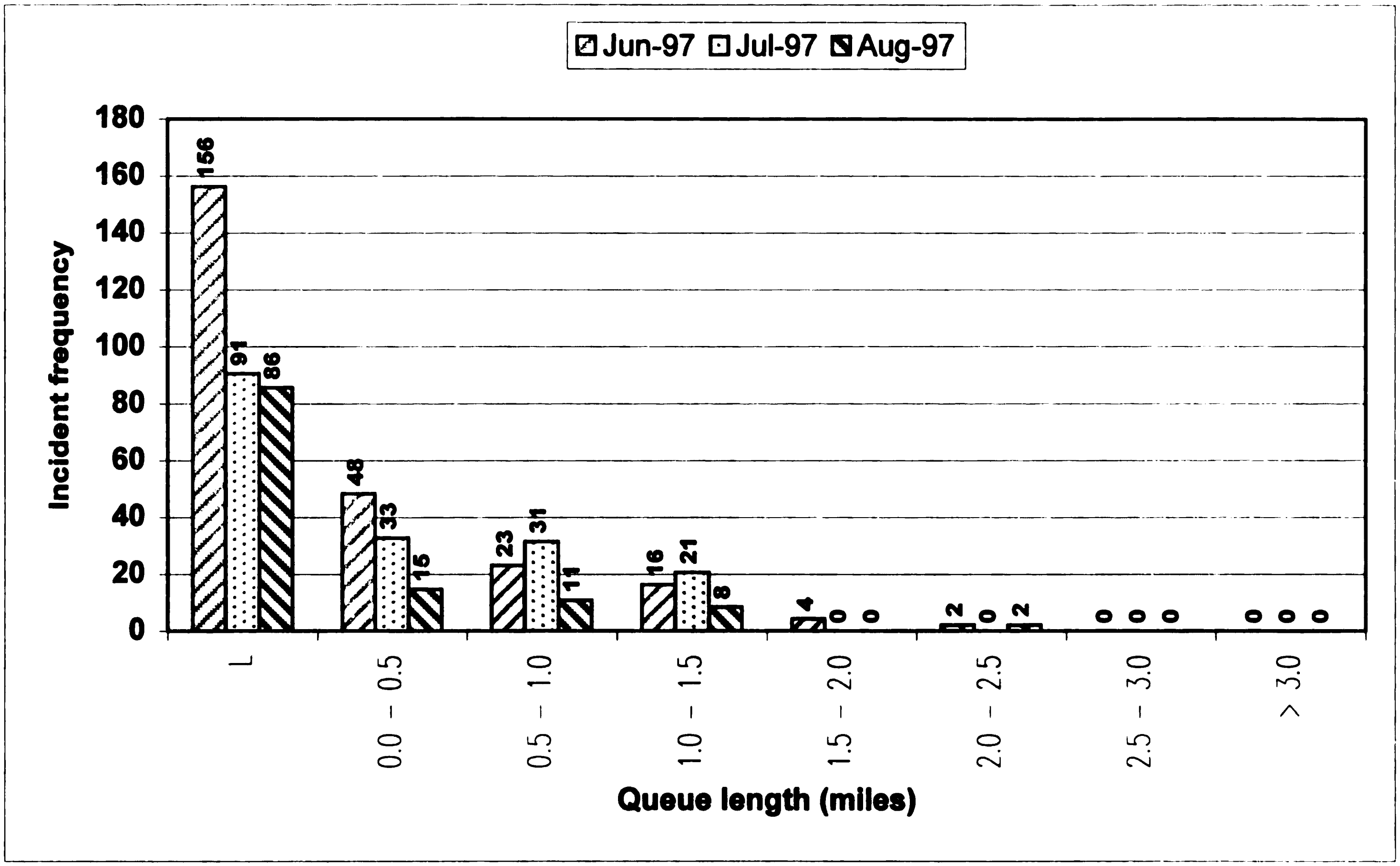


Figure 4.14 System-wide incident frequency by queue length for the months of Jun-97, Jul-97, and Aug-97

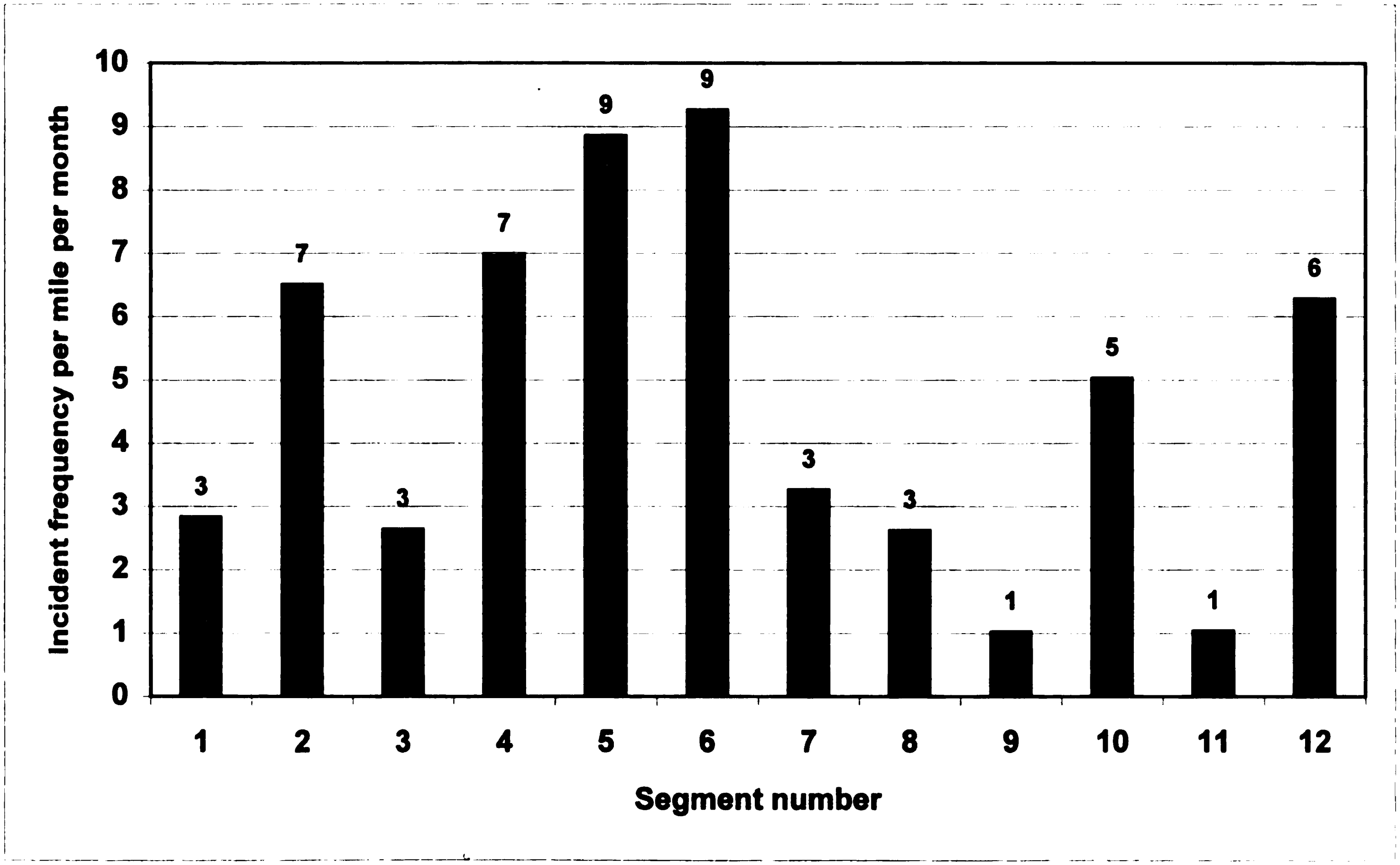


Figure 4.15 Average monthly variation in incident frequency per mile per segment

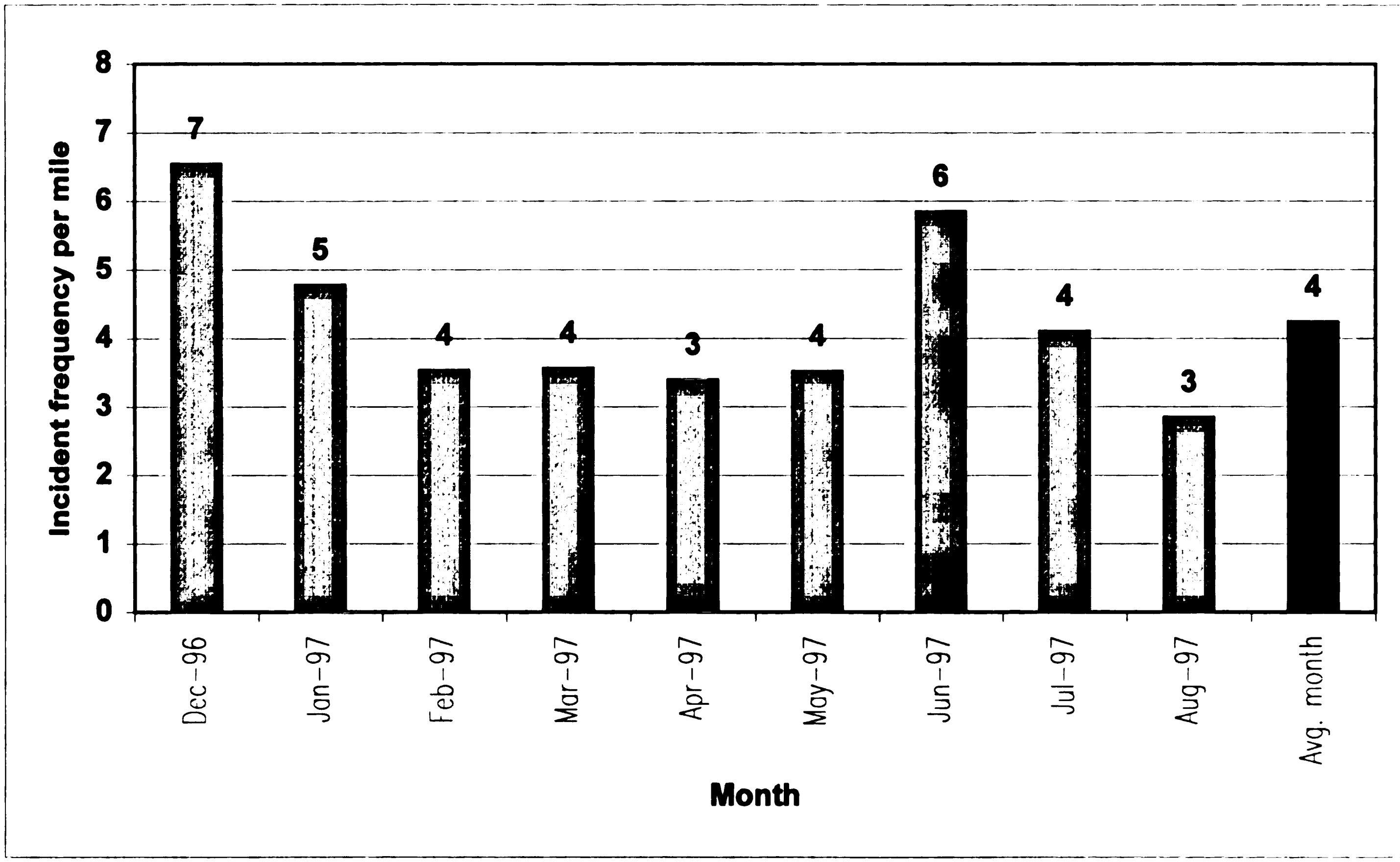


Figure 4.16 System-wide monthly variation in incident frequency per mile

The incident frequency by length of queue for each month was also investigated. Figure 4.17 shows the average monthly incident frequency and queue length. In the average month, 115 incidents which affect one station, and one incident which has a length between 2.0 and 2.5 miles plus a random length described in section 3 of chapter 3 occur over the network.

4.5 Analysis of Traffic Volume

The level of traffic demand has been reported to be one of the factors that correlate to the duration of incident-based congestion. To investigate this correlation, the average daily traffic volume was determined for each detector station. The number of vehicles that passed each detector station at a speed below the threshold speed are then extracted from these data. This section presents the steps followed to calculate and analyze the relationship between the total traffic volume and the traffic volume during congested time periods.

The off-peak traffic volume was extracted for each station by adding the total volume before and after the peak hours. To account for the volume missed due to malfunctioning detectors, the measured volume was factored using the same technique described in section 4.2.1. The factored volume was then converted to vehicles per lane per hour (vplph). The same procedure was applied to the congested volume, where the volume during the periods of incident-based congestion was extracted, then divided by the duration of incident-based congestion and the number of lanes to produce a measure of vplph. This volume was also factored using the same method applied to the total volume.

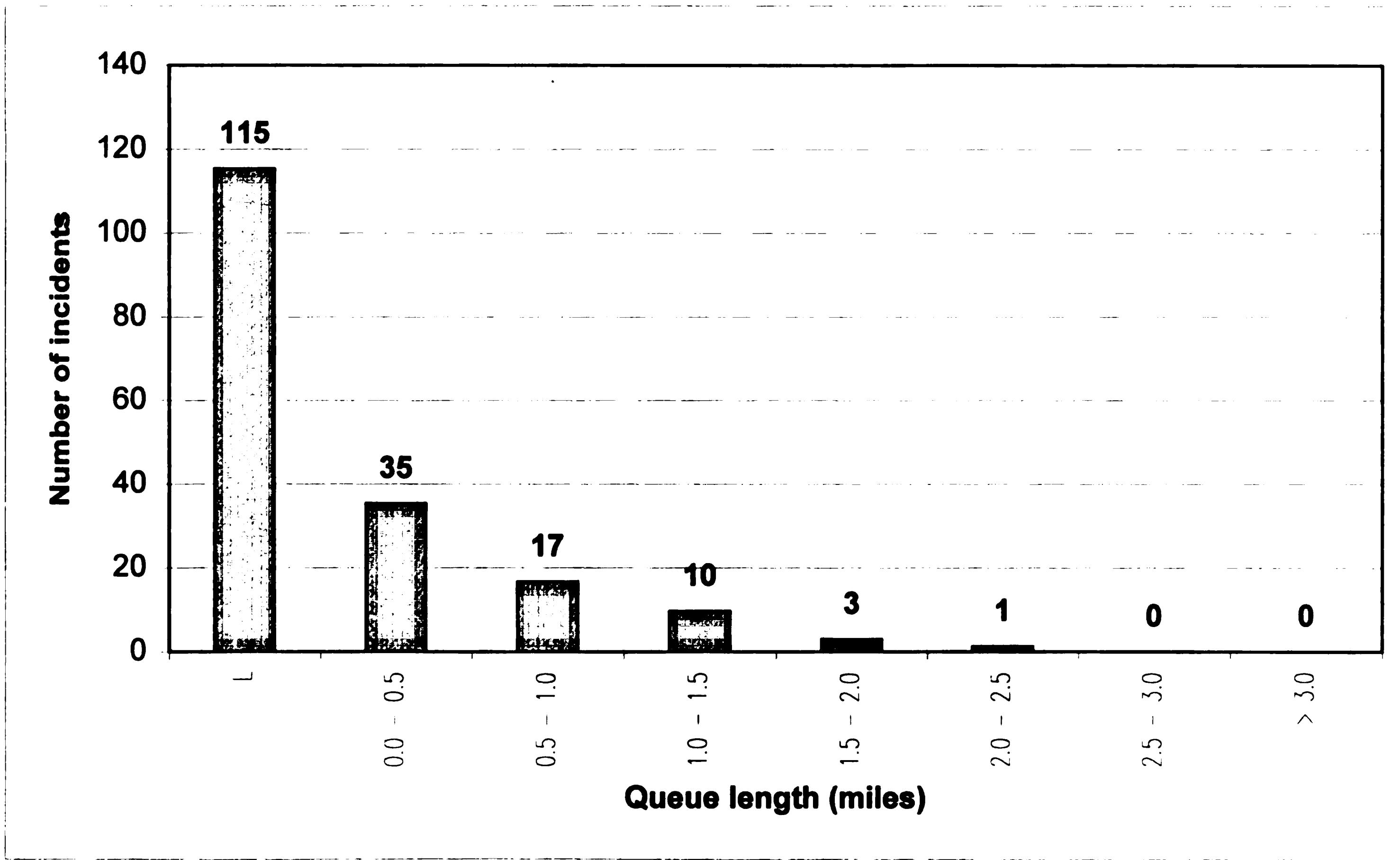


Figure 4.17 Average monthly incident frequency by queue length

The relationship between the incident-based congestion index and the average off-peak volume was investigated for each station, direction of freeway and each freeway as a whole. These relationships are illustrated in figures 4.18 to 4.20. The same procedure was performed using volume data by month and summed by each of the twelve previously defined segments. These relationships are depicted in Figures 4.21 and 4.22. Finally, Figure 4.23 illustrates the relationship between the incident-based congestion index and the nine month average daily off-peak volume for each of the stations involved in this study. If the points with high index values are considered outliers and eliminated from the graph, the slope of the line would have been close to zero indicating the absence of a relationship between off-peak volume and the value of the congestion index.

The relationship between the average monthly incident-based congestion index and the average hourly congestion volume is illustrated in Figure 4.24. This figure also includes the hourly flow for the average month off-peak volume. The total volume was low as was expected because only off-peak hours were considered. The volume during the congested periods was below the capacity for an incident that was located on the shoulder, with the three lanes open to traffic. For incidents where one lane was blocked, the flow would reach the capacity of the opened two lanes. It could be inferred from this graph that the majority of the incidents blocked one lane because there was a measurable reduction in speed. There might have been a few incidents that blocked more than one lane, causing the speed to be reduced even further. Neither the total volume nor the congested volume reflects a strong linear relationship with the incident-based congestion index as shown in the figure.

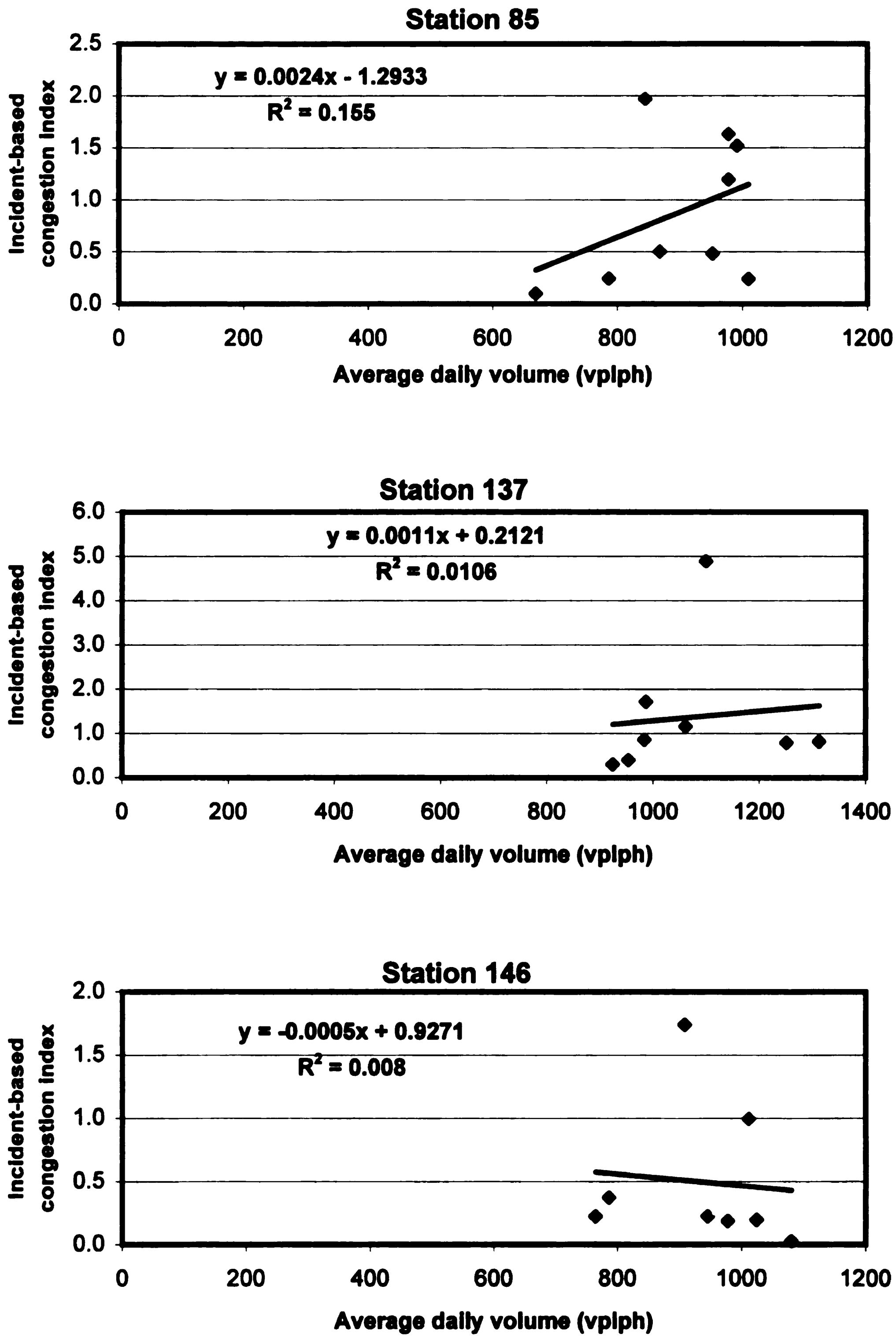


Figure 4.18 Station incident-based congestion index versus average monthly off-peak volume

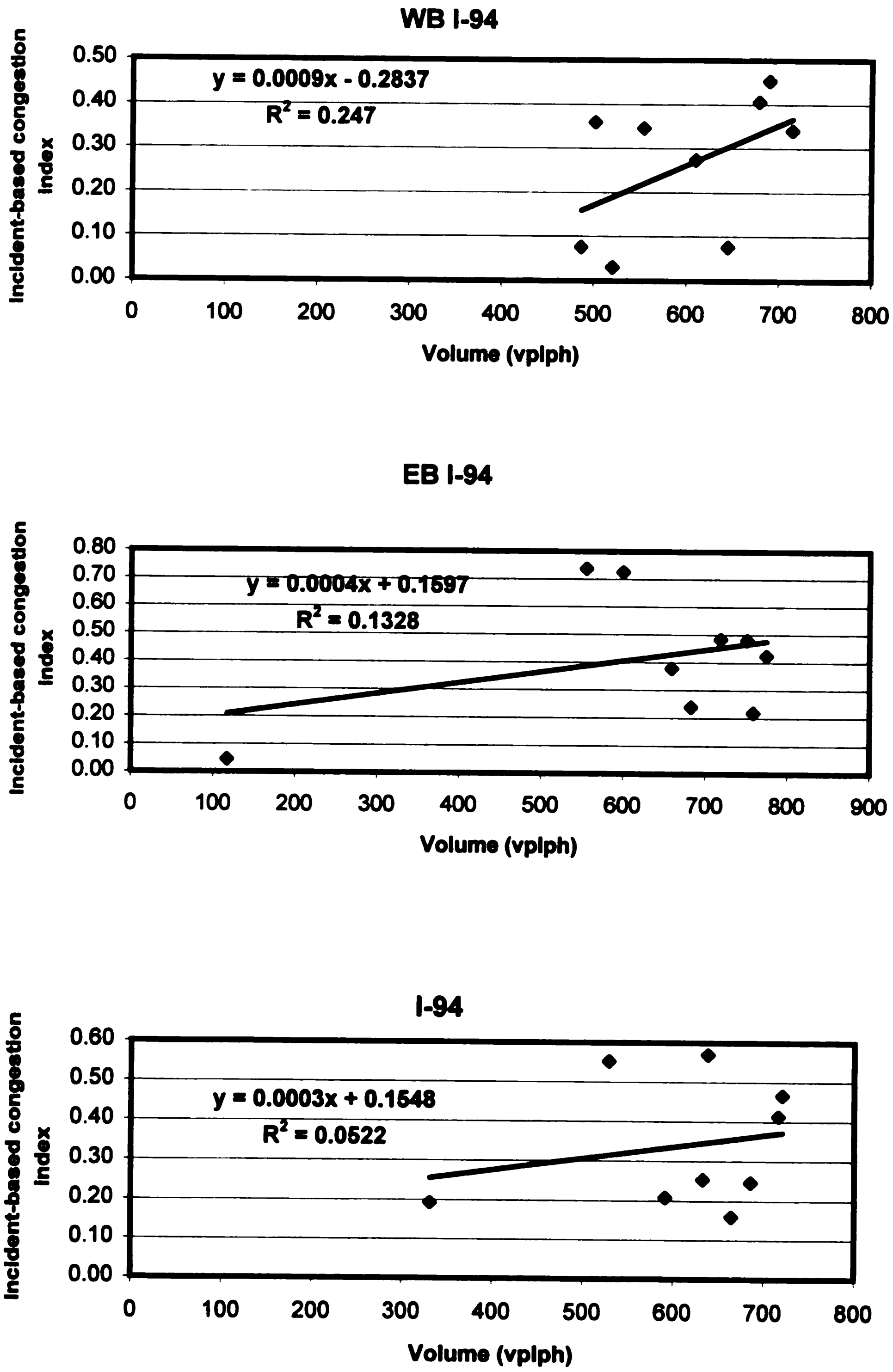
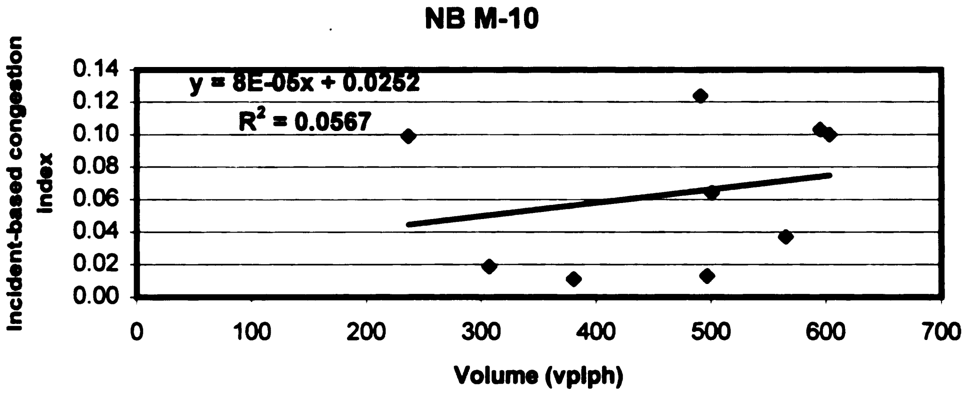
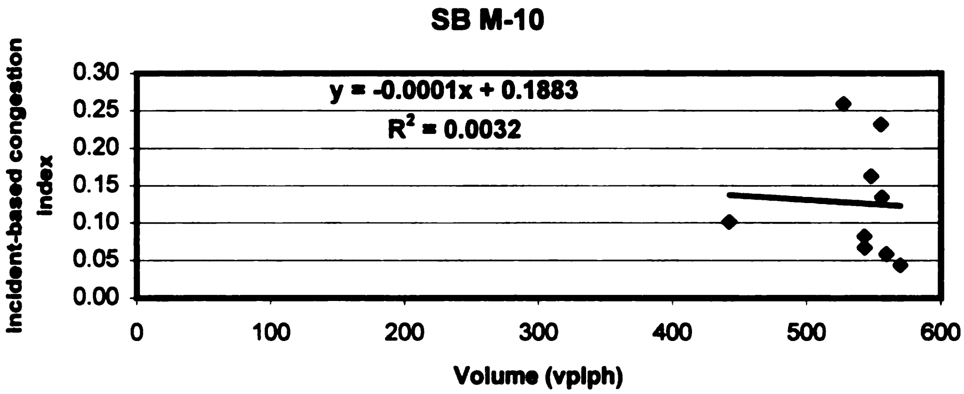


Figure 4.19 Incident-based congestion index versus volume by direction and freeway (I-94)





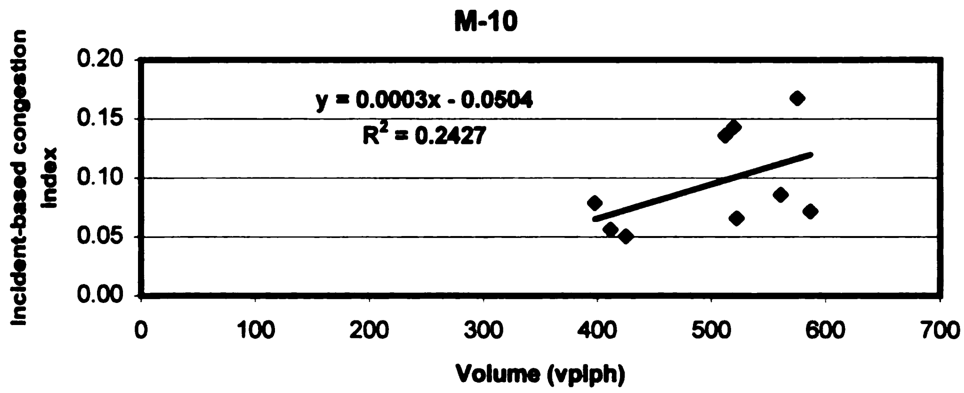


Figure 4.20 Incident-based congestion index versus volume by direction and freeway (M-10)

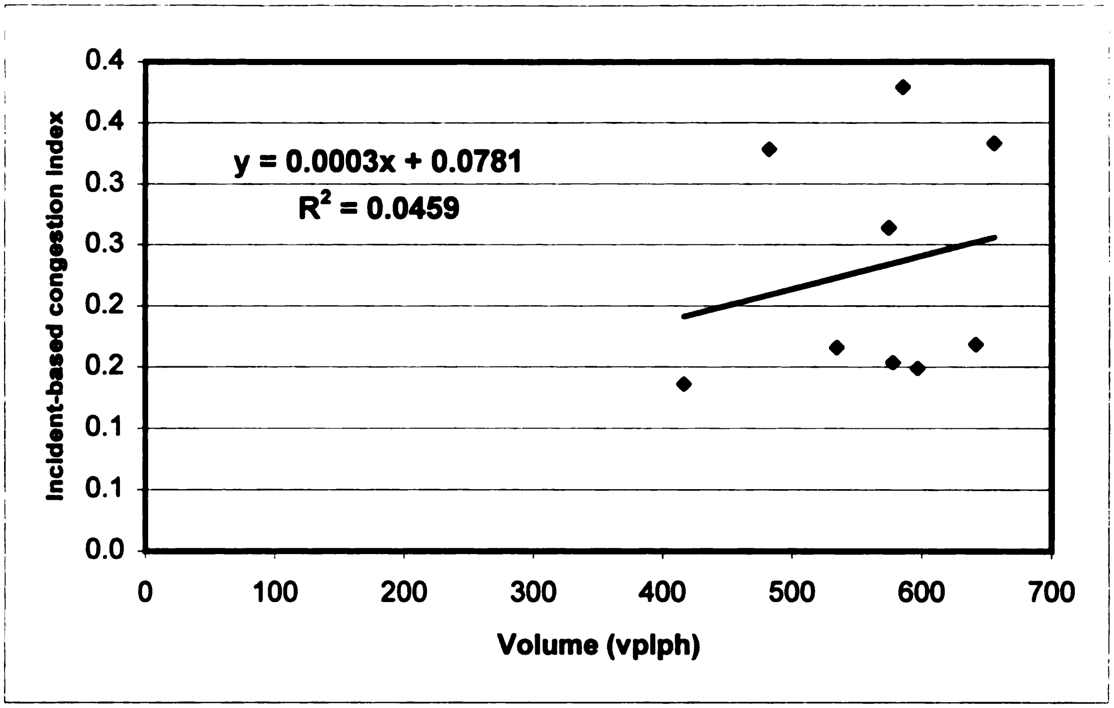


Figure 4.21 Incident-based congestion index vs average monthly off-peak volume

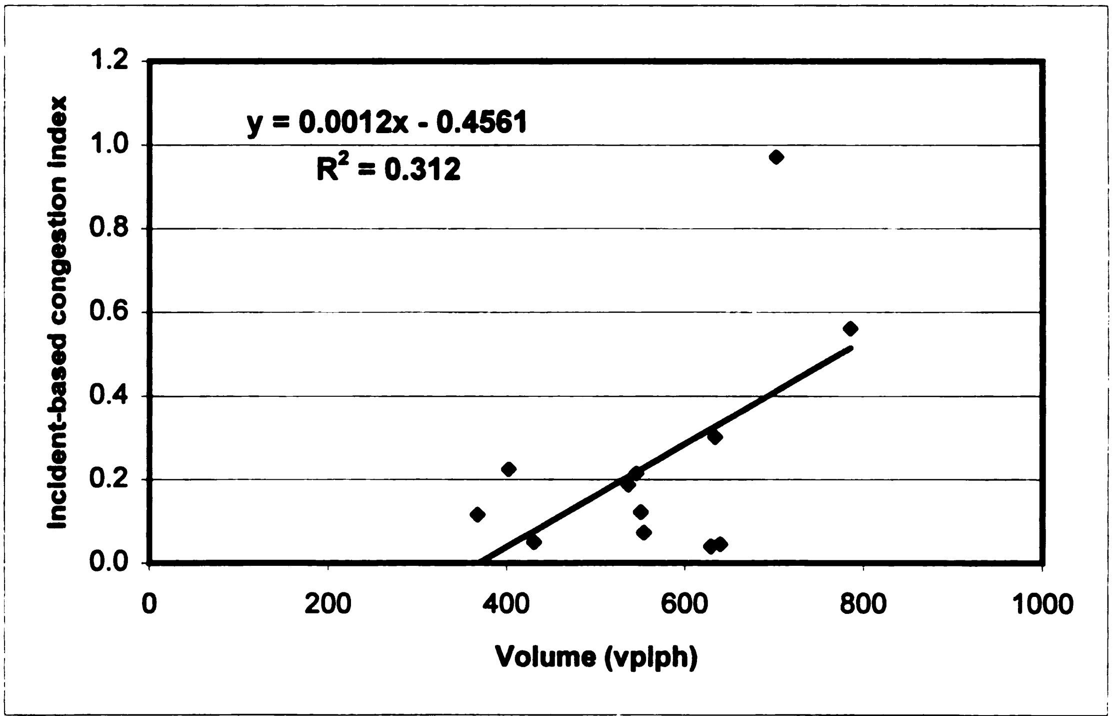


Figure 4.22 Incident-based congestion index vs average segment off-peak volume

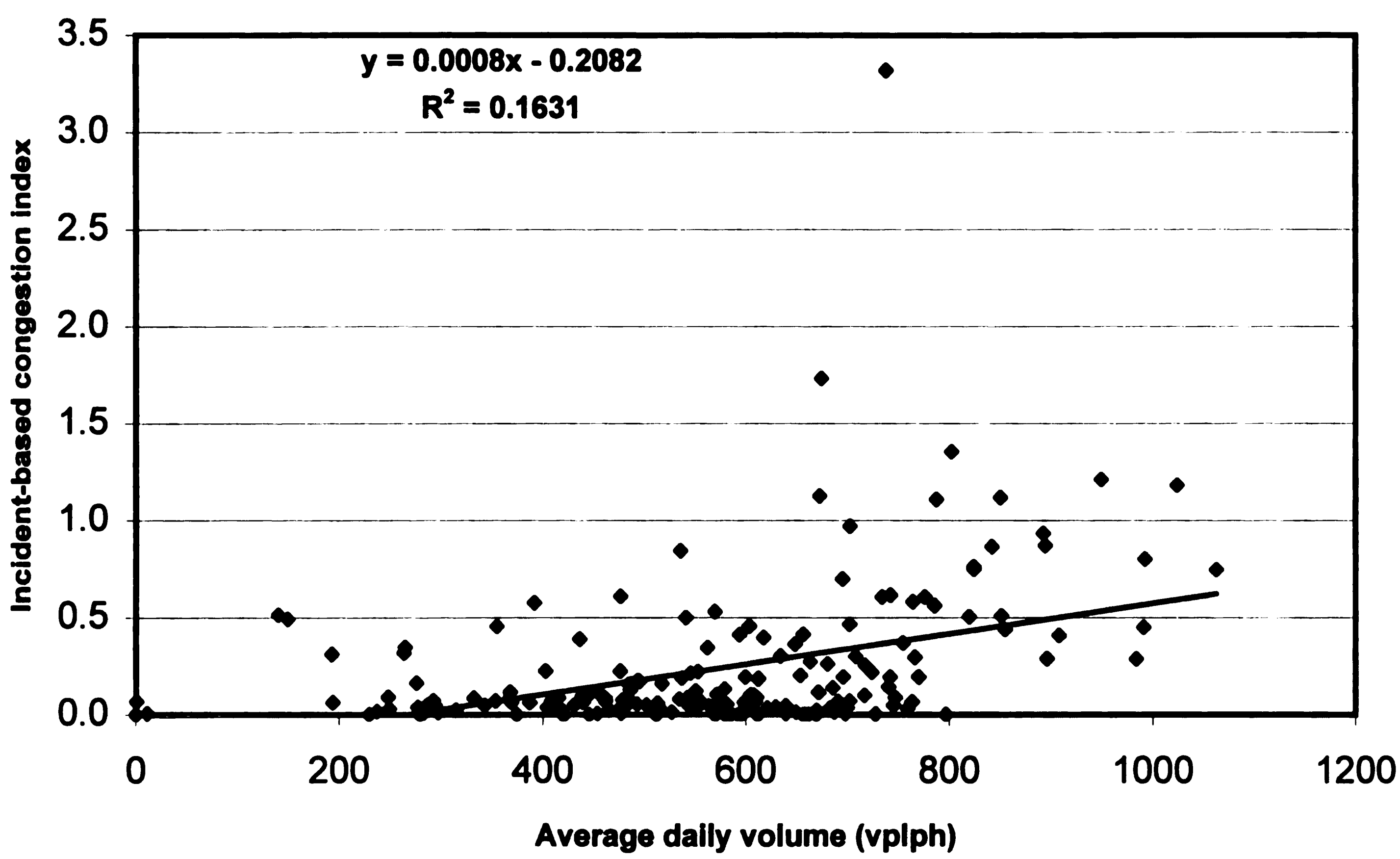


Figure 4.23 Relationship between the incident-based congestion index and the average daily off-peak station volume

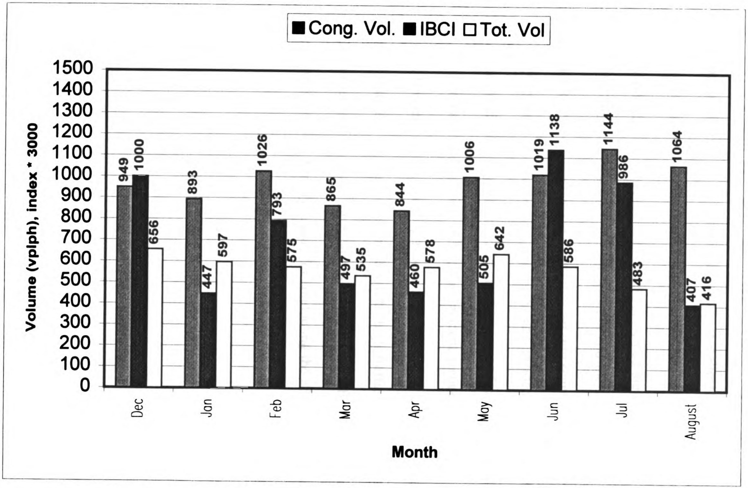


Figure 4.24 Relationship between the incident-based congestion index, congested volume, and average total volume

4.6 Summary

This chapter demonstrated the application of the methodology developed and presented in chapter 3 on the traffic database collected before the ITS deployment program become fully operational. The chapter described the steps performed to yield the basic results to conduct the analysis and presented the results.

The first part described the site location and the freeways involved in this study. It also described how the freeways were divided into segments to isolate the locations and months with high incident-based congestion and incident frequency, and how the data were processed and integrated to yield monthly output files. The results of the analysis of the incident-based congestion index, the incident frequency and the average monthly incident frequency by queue length were then described. The data were then analyzed to identify stations, segments and months with high traffic volume. The purpose of this analysis was to investigate the relationship between traffic volume and the measures of effectiveness values. Finally, a plan for conducting the after analysis was presented.

Chapter 5

Summary and Conclusions

This research study presented the development of measures of effectiveness to evaluate the ITS deployment program in Detroit based on incident-related congestion during off-peak hours. The measures of effectiveness were derived to identify and quantify the frequency, duration, and location of incident-based congestion, and to estimate delay and the characteristics of queues caused by incidents on various segments of the freeway network. Three measures were established to meet these requirements; the first measure quantifies individual station incident-based congestion; the second is a measure of the aggregate impact of individual incidents across stations. This measure also quantifies the incident frequency and queue length. Finally, the third measure is an index that quantifies incident-based congestion at the segment level of aggregation.

The measures of effectiveness were utilized to analyze nine months of traffic data on the SCANDI system before the ITS technologies were implemented. The morning and evening rush hours were excluded from this study.

The station average monthly incident-based congestion index ranged from a low of 0.00 to a high of 3.319 over the 184 stations included in the study. On westbound I-94, station 78 on segment 1 had the highest incident-based congestion index of 1.354, which is equivalent to 14.6 minutes of average daily incident-based congestion. On eastbound I-94, station 134 located on segment 5 experienced the highest incident-based congestion. The index value for the station was 3.319, which translates to 35.8 minutes of average daily incident based congestion. This station had the highest index value among all stations on the network. On northbound M-10, station 177 on segment 7 experienced the highest incident-based congestion of 0.347, which is equivalent to 3.7 minutes of average daily incident-based congestion. On southbound M-10, station 273 on segment 12 experienced the highest incident-based congestion of 0.609, which translates to 6.6 minutes of average daily incident-based congestion.

The segment average monthly incident-based congestion index ranged from 0.971 for segment 5 on eastbound I-94 to 0.039 for segment 8 on northbound M-10. The station average daily duration of incident-based congestion on segments 5 and 8 was 10.5 and 0.4 minutes respectively.

The variation in the average monthly incident-based congestion index ranged from 0.379 for the month of January 1997 and 0.136 for the month of August 1997. The station average daily duration of incident-based congestion in the months of January and August 1997 was 4.1 and 1.5 minutes respectively.

The summer of 1997 demonstrated the highest incident-based congestion among the seasons included in the data, and the spring showed the lowest index value. The seasonal incident-based congestion index was 0.249, 0.162, and 0.281 for the winter, spring, and summer of 1997, respectively, and their corresponding station average daily duration of incident-based congestion was 2.7, 1.8, and 3.0 minutes respectively. On an annual basis the average station index value was 0.23, which corresponds to 2.5 minutes of average daily delay per station caused by incidents.

The incident-based congestion on I-94 was higher than M-10. The index values for I-94 and M-10 were 0.340 and 0.095, which translate to 3.7 and 1.0 minutes of average delay caused by incidents. The directional incident-based congestion index was

0.262 and 0.415 for westbound and eastbound I-94, respectively. These index values are equivalent to 2.8 and 4.5 minutes of average daily incident-based congestion. Southbound M-10 had about twice the value of incident-based congestion as northbound M-10. The directional incident-based congestion index was 0.063 and 0.127 for these two directions. These index values are equivalent to 0.7 and 1.4 minutes of average daily incident-based congestion, respectively.

During the winter and summer, the incident frequency tended to be higher than in the spring. In the winter, there were 635 incidents of various lengths on the network, of which 423 incidents affected one station and 4 had a length between 2.0 and 2.5 miles plus a random length. In the spring, there were 448 incidents of various lengths on the network, of which 282 incidents affected one station and 2 had a length between 2.0 and 2.5 miles plus a random length. In the summer, there were 547 incidents of various lengths on the network, of which 333 incidents affected one station and 4 had a length between 2.0 and 2.5 miles plus a random length.

The segment average monthly incident frequency per mile ranged from 9 incidents for segment 6 on eastbound I-94 to 1 incident for segment 9 on northbound M-10. The system-wide average monthly incident frequency was 4 incidents per mile.

The average monthly incident frequency ranged from 7 incidents per mile for the month of December 1997 to 3 incidents per mile for the month of August 1997. In the average month, there were 181 incidents that occurred system-wide, 115 affected only a single station and one incident extended over 2.5 miles.

The relationship between the off-peak traffic volume and the incident-based congestion index was investigated at the station, segment, direction of freeway, freeway, and the system as a whole level. In all cases, the traffic volume analysis showed that there is no strong linear relationship between the off-peak traffic volume and the incident-based congestion index.

The number of sampling days required to perform the after analysis on the SCANDI system and to perform the before and after analysis on the newly instrumented freeways were estimated seasonally and annually. It is recommended that 25 days of data be collected in the after period if the after analysis is performed seasonally and 40 days if the evaluation is conducted over more than one season (see Appendix A).

The values of the various MOE for incident-based congestion will be determined for the freeway system after the ATMS/ATIS system is fully operational, and the differences will provide one measure of the effectiveness of the system. Other measures will include changes in recurring congestion and traffic crashes.

Appendix A

Appendix A

Plan for Conducting the After Analysis

This research project was conducted to quantify the benefit of the ITS deployment program in the Detroit metropolitan area by assessing changes in non-recurring congestion during off-peak hours before and after the ITS deployment. The results of this study utilized ninety days of traffic data representing the winter, spring and summer of 1997. The number of sampling days required to perform the after analysis on the SCANDI system and the number of days required to perform the before and after analysis on the newly instrumented freeways were estimated seasonally and annually. The estimation methods are described in the following paragraphs.

To determine the sample size required to obtain a reliable estimate of the congestion index, the following analysis was conducted: a) the daily incident-based congestion index was calculated for each of the ninety days and ordered randomly; b) the index was calculated for the first day selected from the random list; c) the index was then calculated for the combination of the first and second days from the list, and this procedure was continued through the ninety days. Figure A.1 shows the cumulative index versus the number of days included in the sample. This figure indicates that the index stabilized after about 40 days. This suggests that if days were sampled randomly throughout this nine months period, 40 days would be required to estimate the system-wide congestion index.

For the seasonal case, the ninety days were divided into three sets of thirty days to represent the winter, spring, and summer. The same procedure used to estimate the

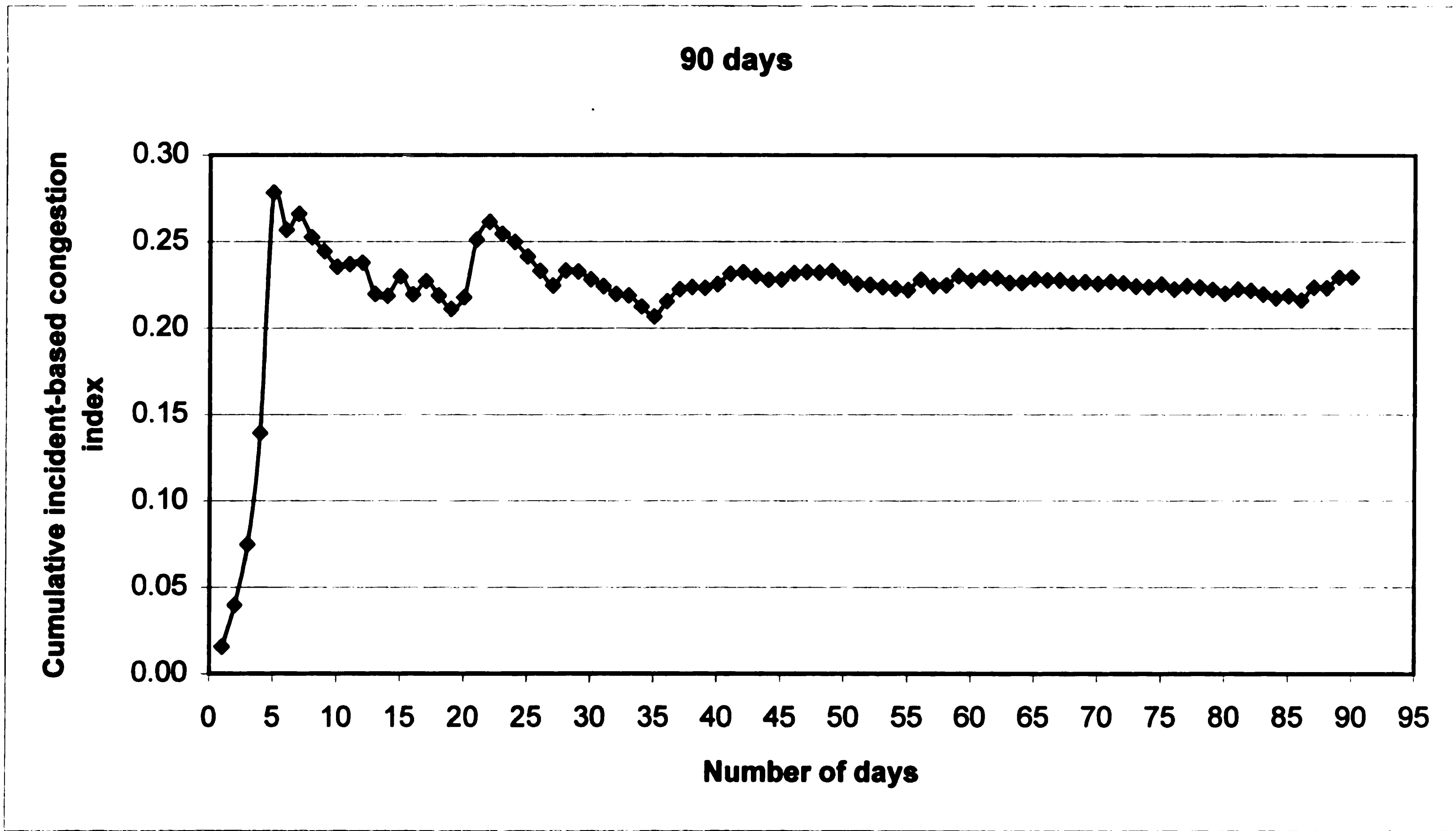


Figure A.1 Annual sampling plan

required sample was applied to each of the three sets. Figure A.2 illustrates the cumulative incident-based congestion index versus the number of sampling days for the winter, spring and summer. This figure shows that the index converged after twenty five days for the winter, spring, and summer.

Based on this analysis, it is recommended that 25 days of data should be collected in the after period if the after analysis is performed seasonally and 40 days if the evaluation is conducted over more than one season. After data is collected for the before and after periods, the before and after analysis will be performed by comparing the means of the incident-based congestion index before and after the ITS deployment. Since the sample sizes are 25 or 40, (n_b, n_a) both distributions can be assumed normally distributed. The test will be conducted by calculating the before and after means (μ_b, μ_a) and standard deviations (σ_b, σ_a) for the incident-based congestion index. With these data, the 95% confidence interval for the difference in population mean indices between the before and after samples will be determined. Given a 5% level of significance, a test will be constructed to determine if there is a significant difference between the population mean indices. Since $1 - \propto = 0.95$, $\propto/2 = 0.025$ and $z_{0.025} = 1.96$. Thus a 95% confidence interval for $\mu_b - \mu_a$ is:

$$\mu_b - \mu_a \pm Z_{0.025}\sqrt{\frac{\sigma_b^2}{n_b} + \frac{\sigma_a^2}{n_a}} \quad \text{.............................. A.1}$$

If the confidence interval includes zero, then the null hypothesis H_o: $\mu_b = \mu_a$ is accepted at the level $\propto = 0.05$ and the alternative null hypothesis H1: $\mu_b \neq \mu_a$ is rejected which means that the deployment had no affect on the incident-based congestion index.

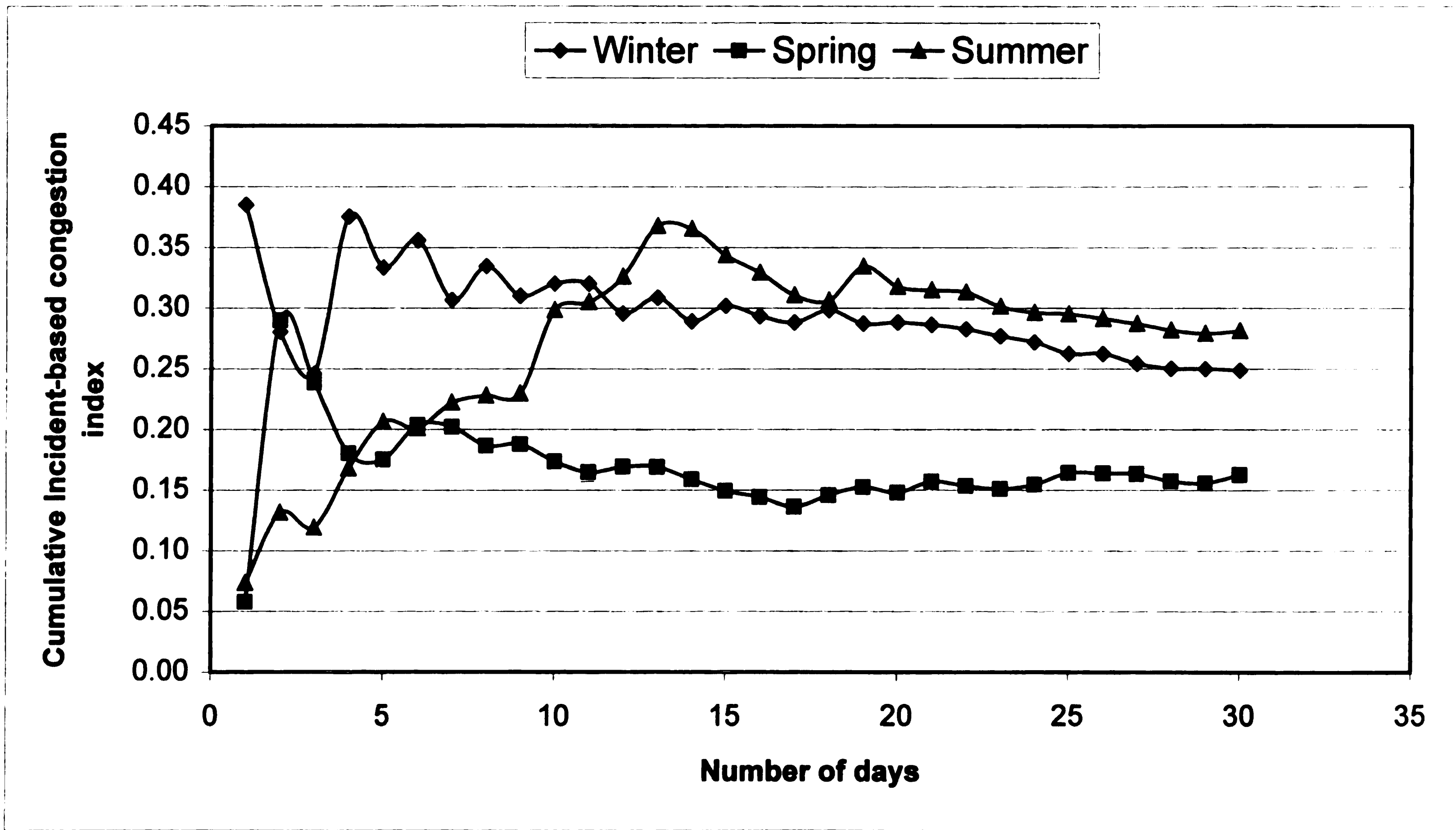


Figure A.2 Seasonal sampling plan

The steps remaining to complete the comparison of the level of congestion before and after the ATMS deployment include:

- Collect 25 days of data on the SCANDI system after the ITS becomes fully operational;
- Using the program developed in this study, process the after data to determine the frequency, duration, and location of incident-based congestion;
- Compare the before and after incident-based congestion index for the SCANDI system in terms of the changes in the incident-based congestion index, incident frequency per mile and average queue length;
- Collect a set of 25 days of both before and after data on the newly instrumented freeway system;
- Analyze the data in the same manner carried out on the SCANDI system;
- Compare the before and after incident-based congestion index for the newly instrumented system in terms of the changes in the incident-based congestion index and incident frequency per mile.

The before and after analysis may be performed in terms of observing the changes in the incident-based congestion index, incident frequency per mile for each station, segment, and freeway, and the system as a whole. Table A.1 illustrates a suggested summary of the before and after comparisons.

Table A.1 Summary of the before and after comparisons

Location	Average index I_b (before)	Average index I_a (after)	ΔI
Station 1 2 . . . 174			
Segment 1 2 3 . . 12			
Freeway I-94 M-10			
System			

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