ABSTRACT

Havel, Jason Robert. A Method for Prioritizing and Expanding Incident Management Assistance Patrols. (Under the direction of Dr. Nagui Rouphail.)

Incident Management Assistance Patrols (IMAPs) enable smooth traffic flow by assisting stranded motorists and aiding in incident clearance. Currently, many large urban areas have IMAP services and the number of urban areas with IMAP programs continues to grow. The expansion of these programs is largely due to the successes of existing programs in the areas of traffic and incident management. However, the decision on where to expand the patrols is becoming ever more difficult as existing criteria typically suggest the high-priority areas that already have IMAP service; furthermore possible benefits of the service are often indistinguishable on lower-priority facilities. This project develops a new approach for identifying locations that can benefit from IMAP service in North Carolina through the use of expanded analyses criteria. Analysis of three incident/crash indices, desired IMAP coverage intensity, and delay estimations are combined to create a comprehensive methodology to evaluate and rank possible IMAP expansion sites. The results of this research were integrated into a decision-support software tool that allows easy assessment of candidate expansion site using planning and operational methods by comparing performance measures between sites, modeling the effects of IMAP on delay, and estimating potential benefits and costs impacts. Through the use of this tool, decision-makers can quickly and easily compare the needs of candidate sites to make an informed, cost-effective decision as to where to provide expanded IMAP service.

A Method for Prioritizing and Expanding Incident Management Assistance Patrols

by

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BIOGRAPHY

Jason Robert Havel was born January 24, 1978 in Cedar Rapids, Iowa. He was raised in Fairfax, Iowa and attended school in the College Community School District from kindergarten through high school. Upon graduation from Cedar Rapids Prairie High School, Jason attended Luther College in Decorah, Iowa where he received a Bachelor of Arts degree in May 2000. While at Luther College, Jason majored in both Physics and Mathematics along with a minor in Computer Science. Upon graduation from Luther College, Jason worked for a computer consulting company in Minneapolis, Minnesota for two years. Then in August 2002, Jason enrolled at North Carolina State University to attain a Master of Science degree in Civil Engineering. This thesis completes the requirements for this degree. After graduation, Jason will work for the transportation engineering firm of Ramey Kemp and Associates in Raleigh, North Carolina.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 – INTRODUCTION

1.1 Background

The National Highway Institute suggests that approximately 60 percent of the existing congestion delay is attributable to incidents (*1*). In response to this trend, Intelligent Transportation Systems (ITS) applications have grown in number and popularity in recent years. Incident Management Assistance Patrols (IMAP) are among the most cost-effective and efficient strategies in dealing with non-recurring congestion resulting from incidents (*2*). An IMAP vehicle typically roams along a corridor in an attempt to quickly locate and respond to incidents in a timely manner. While IMAP vehicles may vary between programs, the general makeup of an IMAP fleet includes vans or trucks capable of carrying various supplies needed to aid drivers. Figure 1.1 shows an example of an IMAP vehicle used in patrolling I-40 between Raleigh and Durham in North Carolina. Among the services provided by an IMAP are: providing gasoline, making minor repairs, removing debris, and assisting with incident clearance (*3*). IMAP vehicles are able to significantly reduce incident durations due to reduced response times as well as the ability to provide special equipment and expertise in the management of incidents in a timely manner (*4*). An important reason that IMAP programs are so successful is the magnitude and diversity of the benefits they provide. These benefits include motorist assistance, reduction in incident-induced delay, higher throughput, improved safety (as a reduction in secondary incidents), fuel savings, and lower emissions. Additionally, IMAP vehicles have been shown to have an effect on the reduction of shoulder accidents in North Carolina (*5*).

Figure 1.1 – North Carolina IMAP Vehicle

Due to their largely impressive benefit to cost ratios, IMAP programs have expanded quickly throughout the country since the first program was created in Chicago in the 1960's (*6*). By 2002, in excess of 50% of freeway miles within the largest 78 metropolitan areas in the United States included IMAP patrols along with nearly 20% of freeway miles in the 30 medium-sized urban areas (*7*). While IMAP programs continue to expand, very little development in defining expansion criteria has occurred. Areas experiencing heavy traffic volumes typically are the first to receive service patrols, but incidents in these areas are only a fraction of incidents nationwide. Therefore, there is a need to determine potentially beneficial sites based on criteria beyond traffic volume to include impacts such as incident rates, traffic intensity, and variable program costs.

1.2 Objective

This report focuses on analyzing IMAP programs in North Carolina. North Carolina has a statewide population in excess of 8 million and a mix of urban and rural areas. Primary urban areas in the state have relatively high traffic volumes and congestion and many already have IMAP coverage. In addition, selected rural portions of Interstate 40 and the area surrounding the interchange of Interstate 40 and Interstate 77 in the western, mountainous part of the state also have current IMAP coverage. As the popularity of these IMAP programs has spread, there has been increased pressure to expand services to other areas in the state. However, decision-makers lack a reliable tool that allows them to compare the relative merits of candidate IMAP facilities.

To cost-effectively expand IMAP programs there is a need for an accurate, systematic method for identifying which potential sites should receive the highest deployment priority. Additionally, prioritizing potential sites based on more multiple criteria (rather than traffic volumes only) is especially important as potential sites may have a variety of freeway and incident characteristics. This research addresses the need to place patrols on the facilities where they will have the most beneficial impact on the basis of crash rates, delays, and benefit to cost ratios. In addition, the intensity of coverage is also examined to determine the most beneficial level of IMAP coverage for each site. The methodology developed during this project is implemented in a decision-support tool that compares candidate sites based on planning and operational analyses to determine their viability for IMAP coverage.

1.3 Overview

A literature review is provided in Chapter 2 in order to review previous work related to expansion criteria for IMAP programs. The methodology employed by this project follows in Chapter 3 and describes the progressive approach taken to estimate the impacts of IMAP programs on the performance of potential expansion sites. Analyses include planning level comparison, delay savings estimates, and an annual estimate of a benefit to cost ratio for the site with IMAP coverage. The procedures developed in the methodology are contained in a decision-support software tool that was created for easy comparison of expansion sites, which is described in Chapter 4. This chapter also discusses the results of sensitivity analyses for the example expansion sites to illustrate the impacts of varying IMAP coverage, IMAP vehicle costs, and value of time variables on the benefit-to-cost ratios. Finally, conclusions are drawn and recommendations are provided for future research of IMAP expansion studies in Chapter 5.

CHAPTER 2 – LITERATURE REVIEW

In response to the growing adverse impacts of incidents, most large- and medium-sized cities have initiated incident management programs (*8*). An important part of many incident management programs is freeway service patrols (IMAP). While Chicago has operated an IMAP program since the 1960s, the majority of IMAP programs started during the 1990s (*9*). In addition to larger urban areas, rural areas that have high incident rates and/or roadway configurations that increase the effect of incidents (i.e. hazardous terrain), such as in the Western portion of North Carolina and on the floating bridges in the Puget Sound, have also implemented IMAP programs (*4*).

The goal of IMAP programs is the quick detection and response to incidents in order to restore the freeway to full capacity in a timely matter following the occurrence of an incident. IMAPs in particular focus on the reduction of incident detection and incident clearance times (*1*). A variety of techniques are used to accomplish this goal including offering basic repairs and gasoline, calling for private tow trucks, providing short-range vehicle relocation, and helping to manage traffic around an incident (*3*). Due to the diversity of programs nationwide, varying service levels exist among different IMAP programs. Frequencies in coverage range from a vehicle passing a point on a route every 10 minutes up to once every hour (*10*). It has been shown that factors such as IMAP fleet size, hours of operations, location, and size of the patrol area influence how quickly incidents can be removed from the freeway (*11*). Additionally, the overall level of effectiveness of an IMAP program is dependent on both traffic characteristics (such as number of incidents and type and saturation level) and operational characteristics (such as length of routes and patrolling frequency) (*12*). Despite the range of IMAP program characteristics there is little argument that these programs are beneficial to those affected by their operation. Customers are overwhelmingly supportive of this service because it is free, fast, and it increases their sense of safety on the highway (*2*). Police officers are also pleased because IMAPs create a safer environment around incidents (*13*).

One of the reasons that IMAP programs are viewed so positively is their cost-effectiveness. In a comprehensive study, Fenno and Ogden report that benefit to cost ratios for IMAPs range from 2.1 to 36.2 nationwide (*6*). On a smaller scale, benefit to cost ratios for IMAPs ranged from 3:1 to 58:1 for individual IMAP routes in Massachusetts, resulting in a benefit to cost ratio of 19:1 for the entire program (*12*). One of the important economic decisions facing both new and existing IMAP programs is the decision on hours of operation. A study of the Hoosier Helper program in Indiana found that a 24 hour program operation was more beneficial, with a benefit to cost ratio of 13:1, in contrast with daytime only service with a benefit to cost ratio of 4.7:1 (*14*). In part, the benefit/cost ratio is so favorable because it has been shown that incident management is an effective way to increase roadway capacity by up to 20% without paying for expensive improvements such as increasing physical capacity (*15*).

Most IMAPs constantly patrol a stretch of freeway looking for incidents. Thus, they are typically in close proximity to incidents to which they are dispatched and find many of the incidents themselves. San Francisco/Oakland IMAPs reportedly located 92% of all incidents themselves (*16*) while other IMAP programs nationwide report locating 57% - 95% of all incidents (6). Additionally, effective deployment of an IMAP results in a reduction in both the dispatch and travel times of units (*17*). Various studies have shown that a deployment of IMAP vehicles can reduce response and clearance times of incidents. For lane blocking incidents in the Puget Sound region of Washington the average response time without an IMAP was 7.5 minutes. With a IMAP, response time was reduced over 50% to roughly 3.5 minutes (*4*). Across the nation, IMAPs have been found to reduce incident response times by 19%-77% (*4, 18*). Any reduction in incident detection, response, and clearance times reduces the total duration, which in turn reduces queuing delay (e.g., one minute of response time reduction is associated with approximately 0.6 to 1 minute reduction of clearance time) (*19*). Average incident clearance times were reduced at IMAP sites by 8 minutes and in some cases by up to 1.5 hours (*20, 21, 22*).

An evaluation of the Coordinated Highways Action Response Team (CHART) in Maryland, which includes incident response along with traffic monitoring, traveler information, and traffic management, reported an annual savings of 40.1 million vehicle hours of delay, 398,000 gallons of fuel, and $30.5 million (*23*). The most significant finding, according to the authors, was that the incident response program, supported by traffic surveillance technology, resulted in a 7.5:1 benefit/cost ratio using estimated delay, fuel consumption, and secondary incident reductions.

Georgia's Intelligent Transportation System, "NAVIGATOR", includes incident management patrols, electronic toll collection, signal control, and other ITS innovations (*24*). An evaluation of NAVIGATOR yielded a 30% reduction in identification, response, and dispatch time, a 23-minute reduction in incident duration that saved $44.6 million, and a 3.2:1 benefit/cost ratio for the freeway and incident management components. Other benefits not fully quantified include air quality impact reductions, fuel consumption savings, crash reduction, more efficient use of emergency services, and more satisfied travelers.

Results from the evaluation of nine ITS implementation projects in San Antonio, Texas, indicate that the most effective stand-alone implementation is incident management (*18*). For a particular corridor modeled during this study, implementation of integrated surveillance and incident management resulted in a 5.7% decline in delay, a 2.8% decrease in crashes, and a 1.2% reduction in fuel consumption annually. The study reported that integrated use of incident management, surveillance and arterial traffic control could achieve even higher benefits.

An examination of the Massachusetts motorist assistance program reported benefits from delay savings in excess of $37 million, fuel savings of more than $2 million, and a combined reduction in pollutants greater than $375,000 (*12*). Individual route benefits from delay and fuel savings were as high as $5.2 million and $483,000 respectively. In addition, the authors suggest that the program has reduced the probability of secondary incidents by 11.5%.

Of the literature that was reviewed, four studies mention placement criteria. Tennessee's new HELP program used areas of high traffic volume and the assumption that a benefit/cost ratio for IMAPs in Nashville applies to other urban areas across the state (*13*). However, the report is dedicated to a discussion of planning and training techniques for a successful IMAP-not site selection. Maryland's CHART evaluation determined that the incident management program is located in the areas of greatest need by comparing vehicle miles traveled, incidents, non-recurring delay, and incidents per mile against the averages for non-CHART roadways (*23*). However, the results do not indicate whether CHART routes cover segments that have relatively low-levels of need and/or do not cover segments with high-levels of need that deserve patrols. Ohio has a list of seven freeway service patrol warrants that include minimum freeway volume, volume-to-capacity ratio, and crash frequency for implementation of a new program (*26*). Still, these warrants make no suggestion as to the benefits or costs of the placement of a program at the location. In addition, the warrants do not prioritize sites, but rather provide only a check-off system to determine if freeway service patrols should be considered.

Only a single study to date has attempted to address the issue of benefit and cost figures for the expansion or creation of an IMAP program. Researchers in California developed models to predict the number of incident assisted by IMAPs and then estimate the delay, fuel, and emissions savings per incident assisted by the IMAP (*27*). Davies, et al forecasted the number of incidents using Equation 2.1 with 11*MVMT-Served and 35*MVMT-Served as the minimum and maximum constraints, respectively. These constraints limit the estimated number of incidents potentially served by IMAP on both the high and low end based on the MVMT-Served.

$$FWY - INC = 2.4851 MeanLanes + 14.0223 MAADT + 17.7281 MVMTServed - 0.1033 PercentLtShdr$$
(Equation 2.1)

Where:

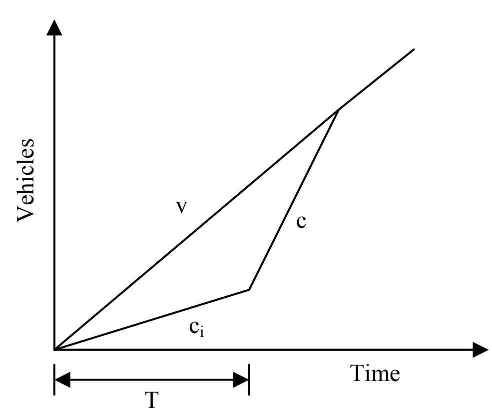
FWY-INC	= Daily freeway-incidents potentially served by IMAP
MeanLanes	= Mean number of traffic lanes including HOV-lanes (one-direction)
MAADT	= AADT/1,000,000 (average annual daily traffic, million vehicles)
MVMTServed	= Daily VMT served by IMAP service (million vehicle-miles)
PercentLtShdr	= Proportion of the beat with a left shoulder (%)

The relationships derived by simulation were then used to approximate the proportion of freeway incidents assisted by an IMAP, resulting in IMAP-assists. Delay caused by each incident is then estimated using the equation:

$$D = \frac{(v - c_i)(c - c_i)T^2}{2(c - v)}$$
(Equation 2.2)

Where:

D	= incident delay (veh-hrs)
c	= capacity (vph)
v	= demand (vph)
c_i	= remaining capacity due to incident (vph)
T	= incident duration (hrs)



One of the key components of Equation 2.2 is the incident duration. To determine the incident duration without an IMAP present, an average service time of 20 minutes was used for all incidents and added to the response time which the user must input (with a default value of 30 minutes). Response time assuming the presence of an IMAP was computed as follows:

If $[(V_{IMAP}T_A) > \frac{2L}{N}]$ Then

$$E[RTR] = T_A - [\frac{L}{(NV_{IMAP})}]$$

Else

$$E[RTR = [\frac{V_{IMAP}(T_A)^2 N}{4L}]$$

Where:

E[RTR]	= expected response time reduction (hours)
V_{IMAP}	= mean speed of the IMAP tow-truck (mph)
T_A	= mean response time without the IMAP program (hours)
L	= length of the beat (miles)
N	= number of IMAP tow-trucks on the beat

A value for V_{IMAP} is entered by the user (with a default value of 45 mph). Total incident duration assuming the presence of an IMAP is then simply the response time entered by the user, less E[RTR], added to the 20 minutes assumed service time. The delay with an IMAP is then determined with the delay equation and the delay savings due to the presence of an IMAP is simply the difference of the delay calculations with and without an IMAP. Fuel and emissions savings are calculated from the incident delays in addition to the fuel and emissions factors derived by the EMFAC7 model (*27*). Delay, fuel, and emissions savings are then multiplied by a monetary value to establish the estimated benefits. Finally, the cost of the IMAP service ($/truck-hr) is entered by the user and an estimated program cost is calculated as follows:

$$\frac{\textit{Time-period costs}}{\textit{day}} = \left(\frac{\textit{\# tow-trucks per}}{\textit{timeperiod}}\right) * \left(\frac{\textit{service hrs}}{\textit{timeperiod}}\right) * \textit{(Cost of IMAP)} \qquad \text{(Equation 2.3)}$$

$$\textit{Daily Costs} = \textit{Sum of time-period costs} \qquad \text{(Equation 2.4)}$$

$$\textit{Annual Costs} = \textit{(\# service days)} * \textit{(Daily Cost)} \qquad \text{(Equation 2.5)}$$

Given the calculated annual benefits and costs, a benefit to cost ratio is readily determined.

The study conducted by Davies et al is among the first to attempt to quantify the benefits and costs of expanding IMAP services. However, the results are based entirely on California data and may not be generally applicable to other areas. In addition, IMAP response times are based on the total length of the facility and the numbers of trucks, when in actuality IMAP vehicles are often able to turn around at various locations within the facility, reducing the response time. Finally, the methodology utilized by the study makes use of only a single, generalized incident (i.e. constant service time) that is based on all incidents affecting the shoulders or a single lane. This does not allow users to view the impacts of the variety of incidents that likely will occur on the facility.

A review of the existing literature on IMAP programs, and especially the expansion of IMAP programs, has resulted in several findings. IMAP programs are widely viewed as a beneficial and cost-effective way of handling incidents and dealing with growing congestion nationwide. However, studies on IMAP programs have focused almost entirely on current programs with very little discussion of possible benefits of expansion sites. Of the few papers that cover this issue, only one discusses the estimated impacts of implementing new IMAP routes, and with many issues unanswered. Clearly more research is needed into the area of quantifying the estimated benefits and costs of expansion routes for North Carolina IMAP programs.

CHAPTER 3 – METHODOLOGY

The overall layout of the methodology, displayed in Figure 3.1, is made up of three main sections including Data, Planning Level Analysis, and Operational Level Analysis. Smaller components can be found within these sections that describe the individual steps completed in the methodology. Finally, the three main sections are then implemented by the decision support tool (discussed in Chapter 4) to provide analysis of an IMAP site. This methodology is based on the methodology developed for the NCDOT project (*32*) on which much of this thesis was based.

3.1 Data

The Data section of the methodology represents both statewide and site-specific data. These data represent the foundation of the methodology and serve as the basis for the Planning Level and Operational Level sections as well as the Decision-Support Tool.

Statewide Historical Data are those data pertaining to crash and traffic characteristics of freeway segments throughout the state of North Carolina. Specifically, these data include crash location, AADT, and number of lanes data from two separate data sources, the North Carolina Highway Safety Information System (NC HSIS) and North Carolina Department of Transportation (NCDOT). NC HSIS is a relatively high-quality database containing information on North Carolina roadway inventory and crashes that is maintained at the Federal level. However, through analysis of the data it was determined that the crash data

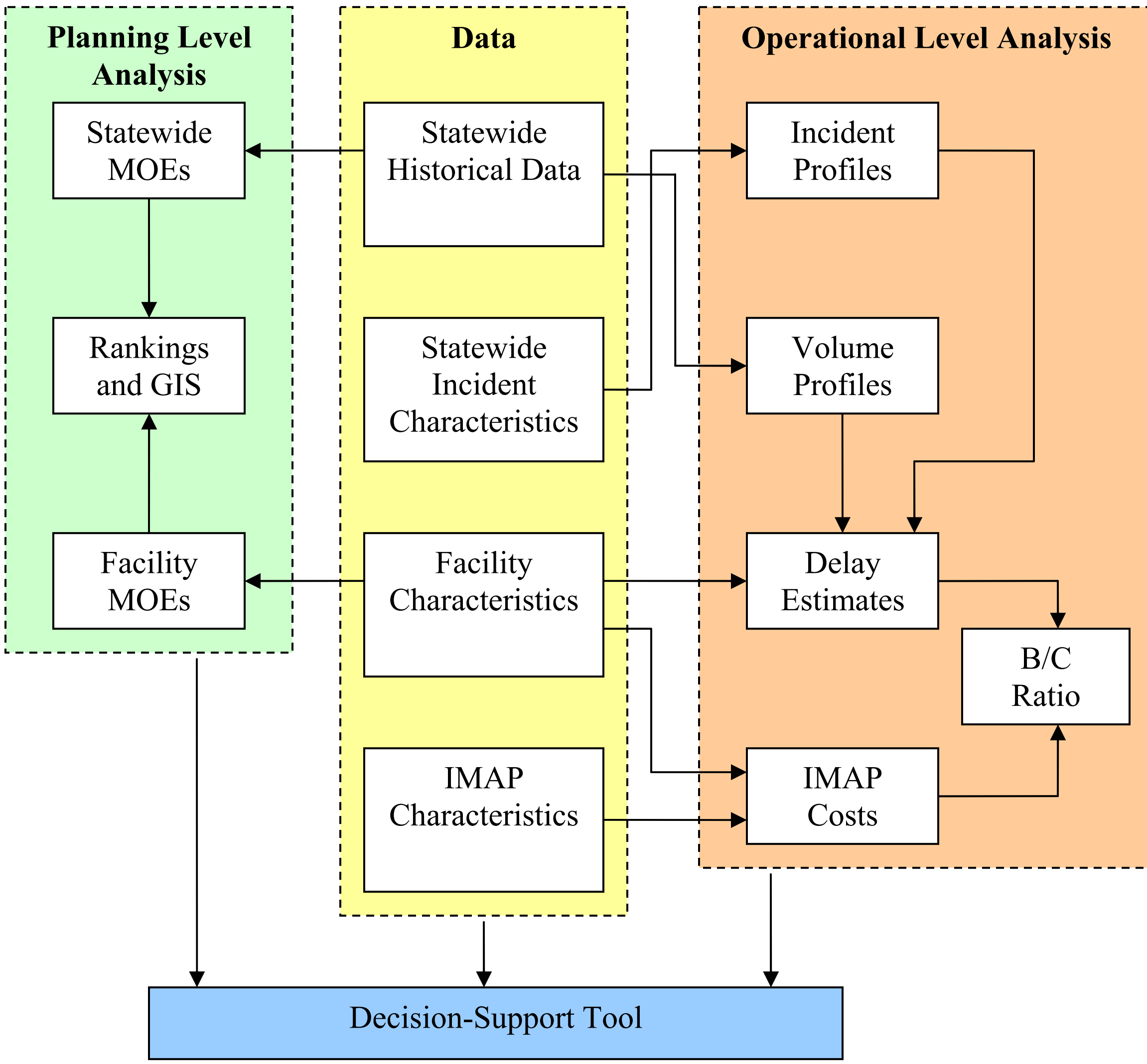


Figure 3.1 – Methodology Flow Chart

provided by NC HSIS was not as complete as similar data from NCDOT and therefore only the roadway inventory data from NC HSIS were used. NCDOT provided crash data with location information in addition to traffic volume data from 30 permanent automatic traffic recorder sites on freeways throughout the state. Data provided by NCDOT were comprised of crash and traffic data from January 1, 1997 to December 31, 1999 and resulted in information related to 49,000 freeway crashes. In addition, NCDOT data included the location of existing IMAP installations in the state as well as Geographic Information System (GIS) shapefiles, allowing for spatial presentation of the data.

To determine Statewide Incident Characteristics, incident data were collected for two IMAP sites in Charlotte and Greensboro from March to May of 2003. These data included the severity, duration, time period, and location of incidents that occurred. Once these data were collected, they were compiled and adjusted to represent annual values (*32*). It should be noted that no annual incident data were available. It is possible that annual incident characteristics may differ from those represented by the data that was collected. However, it is expected that the ratio of incident types will not change significantly on an annual basis from those suggested by the data that were collected. Additionally, it is possible that the relatively good weather that occurs during the months of March-May could actually underestimate the number of incidents that may occur during months that typically have more extreme weather (i.e. the extreme heat of the summer months or winter months that may have snow and ice). An underestimate of the number of incidents would result in an underestimate of the annual benefits that the IMAP program would provide.

Facility Characteristics are data relating to a specific facility that is being examined. These data are collected from information on the facility and include facility length, AADT, annual number of crashes, area type, number of lanes per direction, directional distribution (as a percent), peak hour factor (PHF), value of time, average distance between turnaround points, and response time without IMAP. The average distance between turnaround points describes the estimated average distance between points on the facility where an IMAP vehicle can change directions and may include interchanges or median crossings. Response time without IMAP is the estimated average time it takes for a non-IMAP vehicle, such as a tow truck or police officer, to respond to an incident on the facility.

The IMAP Characteristics component of the Data section is comprised of data related to the existing or projected IMAP installation on the facility. These include the average operating cost per hour for an IMAP vehicle, the hours of operation, and the annual number of days of operation for roaming IMAP vehicles. It is important to note that IMAP installations in North Carolina maintain IMAP vehicle fleets that are larger than the number of vehicles that are roaming within the facility at any given time. Therefore it is critical to note that the number of roaming vehicles represents the average number of vehicles that are actually roaming the facility at any given time while the fleet size conveys the total number of IMAP vehicles that are available for the facility. IMAP installations in North Carolina typically have one-half of their fleet size roaming on the facility during hours of operation.

3.2 Planning Level Analysis

Planning level analysis of a potential or existing IMAP facility allows for a broad comparison of the site, relative to the rest of the state of North Carolina using measures of effectiveness (MOEs) pertaining to traffic and crash levels. The analysis implemented for this research, based on HCM2000 principles (*30*), was developed by Khattak, et al (*28*) and a summary of this planning level methodology can be found in Appendix A. This analysis represents a first screening of expansion sites and includes a general comparison of the facility to statewide facilities. However, it is not a substitute for looking at incident delay benefits or the operational analysis.

3.3 Operational Level Analysis

The analysis at the Operational Level examines the annual costs and benefits of an IMAP installation on the given facility. This analysis is based, when possible, on the procedures provided by the HCM2000 (*30*). Because IMAPs are designed to respond to incidents that occur on the facility, the breakdown of incident types, including the frequency of each incident type that is expected to occur annually, must first be determined in the Incident Profiles component of the Operational Level Analysis. A breakdown of incidents estimated to occur on the facility is determined through a two-step process that includes an incident to crash prediction factor, and incident distribution tree developed from data from the Statewide Incident Characteristics component of the Data section. Firstly, the total annual number of incidents is estimated by multiplying the number of annual crashes by a crash prediction factor of 7.2 derived from North Carolina data by Khattak, et al (*28*). The crash prediction factor relates the number of expected incidents to the number of crashes that are reported. This figure is very comparable to the ratio of 9:1 suggested by Cambridge Systematics (*29*). With the knowledge of the number of crashes occurring on every road segment in the state and the ratio between crashes and non-crashes, it is possible to predict the number of non-crash incidents.

A limitation of this research is the underlying assumption that incidents occur independent of other incidents. This assumption means that when the delay is estimated for an incident, only the incident being examined is considered and the presence of other incidents on the facility at the same time is ignored. This means, in turn, that any effects from other incidents will not be taken into account in this estimation of delay. Additionally, the assumptions made by this research do not account for an incident rate or IMAP response rate. In other words, no effort was made to model how incidents occur in relation to one another (such as total incidents per hour or a breakdown of incidents per hour by severity) or how many incidents per hour can be handled by the IMAP vehicles. Actual IMAP programs must take into account the incident rates for the facility and must plan the number of IMAP vehicles accordingly. Queuing theory is one method that may be used to model estimated delay based on the incident rate and number of IMAP vehicles. However, due to the lack of incident data for North Carolina, it is difficult to estimate incident rates with any accuracy. Agencies that have incident data available may wish to model how incidents occur in relation to one another and the delays that result with queuing theory. Given this limitation of the research, the actual benefits of IMAPs are expected to be greater than the benefits estimated in this effort.

Delay Estimation

The delay resulting from an incident is dependent on several factors related to facility and incident characteristics. In general, delay that is caused by queuing from an incident can be modeled using the demand volume, incident capacity, and normal capacity for the facility. A generalized delay estimation model is shown in Figure 3.2. Additionally, the overall incident duration affects the amount of delay as the incident duration is the amount of time during which the facility operates at a lower capacity (i.e. incident capacity). The incident duration is made up of two separate parts, response time and clearance time. Response time represents the amount of time that is required for the appropriate agency (IMAP vehicle, highway patrol, etc.) to respond to the incident once they are made aware of the incident. Clearance time represents the amount of time that is required to clear the incident from the roadway or shoulder once the responding agency has arrived. Once the incident has been cleared, any remaining queue clears at the capacity rate of the facility.

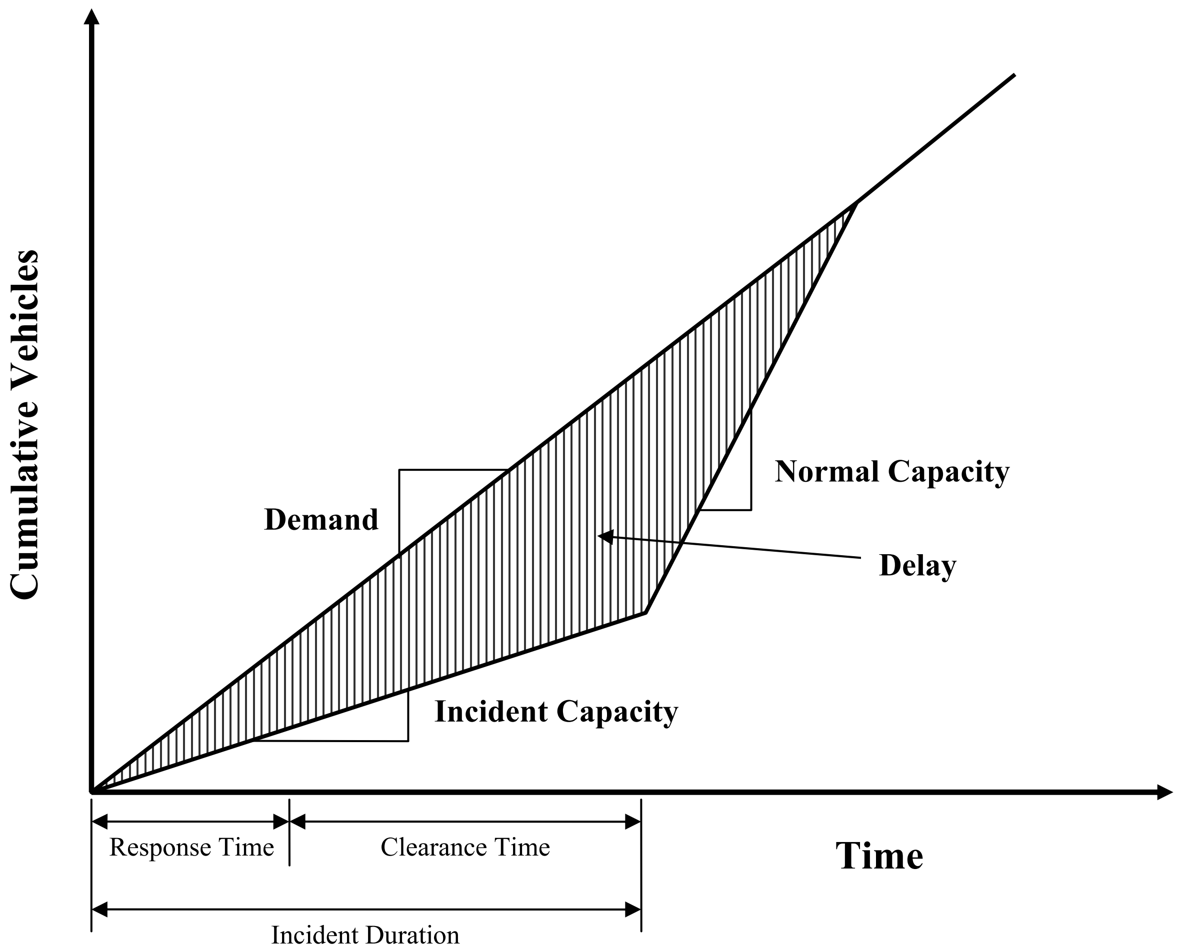


Figure 3.2 – Generalized Delay Estimation Model

Incident Distribution

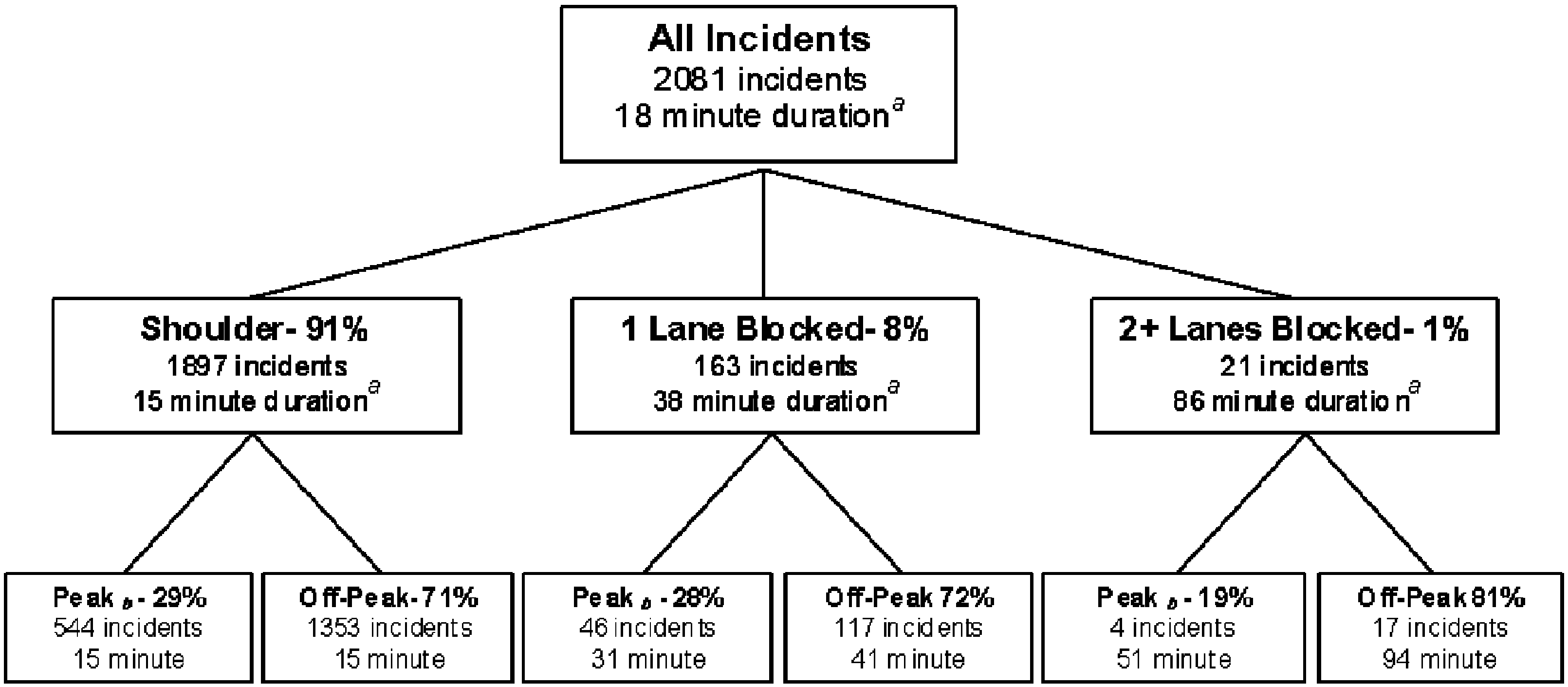
Once the total number of forecasted incidents is determined, a breakdown by incident types is needed so that the total incident duration for each incident type can be estimated. Data from the Statewide Incident Characteristics component of the Data section were used to separate incidents by incident type (shoulder, single lane blockage, or two or more lane blockage) and the time of day of the incident (peak or off-peak). Peak hours include two peaks per weekday and are assumed to be Monday- Friday, 7 – 9 am and 4 - 6 pm. The estimated distribution of incidents is found in the incident distribution tree displayed in Figure 3.3 and is based on incident data from Charlotte and Greensboro IMAPs. Once this breakdown had been determined, the percentage of total incidents of each incident type and average duration were determined for each incident type, and can be found in Figure 3.3.

After the annual distribution of incidents had been determined, a method was needed to determine the percentage of AADT on the facility for various times during the day. To do this, the Volume Profiles component combines data from the Statewide Historical Data component into volumes profiles. This was done by plotting percentage of AADT versus the hour of the day for the facilities represented by the data. These graphs were then separated for rural and urban area types so that similar traffic trends would be combined. Finally, the average hourly AADT percentages for each area type were plotted. The individual plots as well as the average plot for each area type can be found in Figures 3.4 and 3.5. It can be seen from these figures that there is a dual-peak trend in the urban graph (Figure 3.5) that is consistent with volume profiles developed by other studies (*12, 31*). To make these graphs easier to use, the plots were broken down into time periods and an average AADT percentage was assigned to the time period. These breaks were determined simply by viewing the graphs and dividing them into periods with similar AADT percentages. The results of this process can be found in Figures 3.6 and 3.7 for rural and urban area types, respectively.

The next step of the methodology was the Delay Estimation component of the Operational Level section. This used the Facility Characteristics as well as implemented the Incident Profiles and Volume Profiles that had previously been developed. The Delay Estimation component consists of two steps: the development of delay models using FREEVAL software and the implementation of these models in estimating delay for a single incident.

FREEVAL Simulation

FREEVAL is a software program designed to analyze freeway facilities by faithfully replicating the freeway facility methodology in Chapter 22 of the 2000 Highway Capacity Manual (*30*). This software enables modeling of the effects of incidents on traffic operations in a macroscopic environment. For this study, incident analyses were made for freeway facilities that were 10 miles in length, had volumes containing no RVs, and had constant ramp (on and off ramps) volumes of 300 vehicles per hour. In addition, several facility and



[a]*Average Duration with Freeway Service Patrol*

[b]*Peak periods are assumed to be Monday- Friday, 7 – 9 am and 4 - 6 pm*

Figure 3.3 – Incident Distribution Tree (*28*)

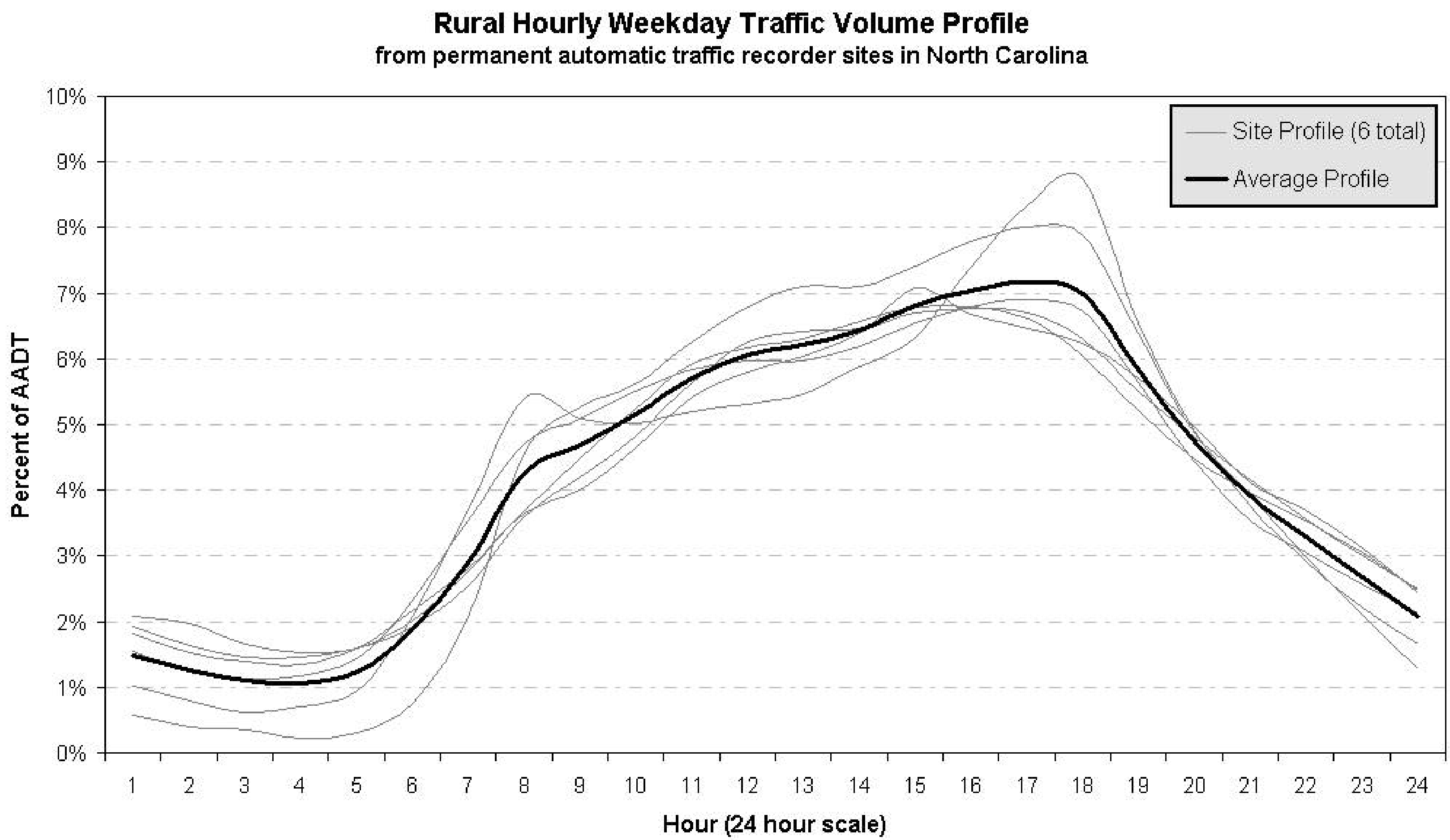


Figure 3.4 – Rural Traffic Profile (*28*)

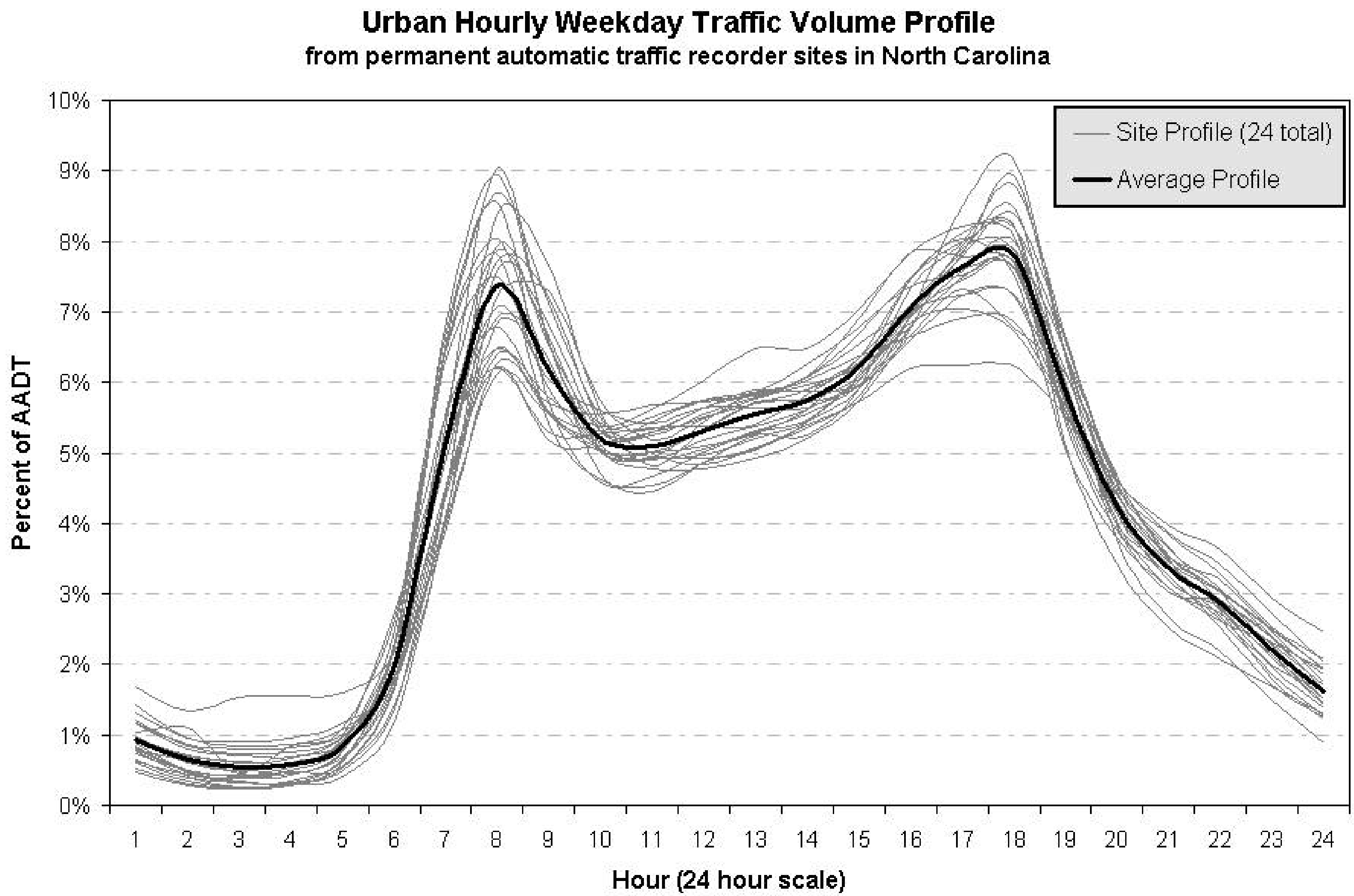


Figure 3.5 – Urban Traffic Profile (*28*)

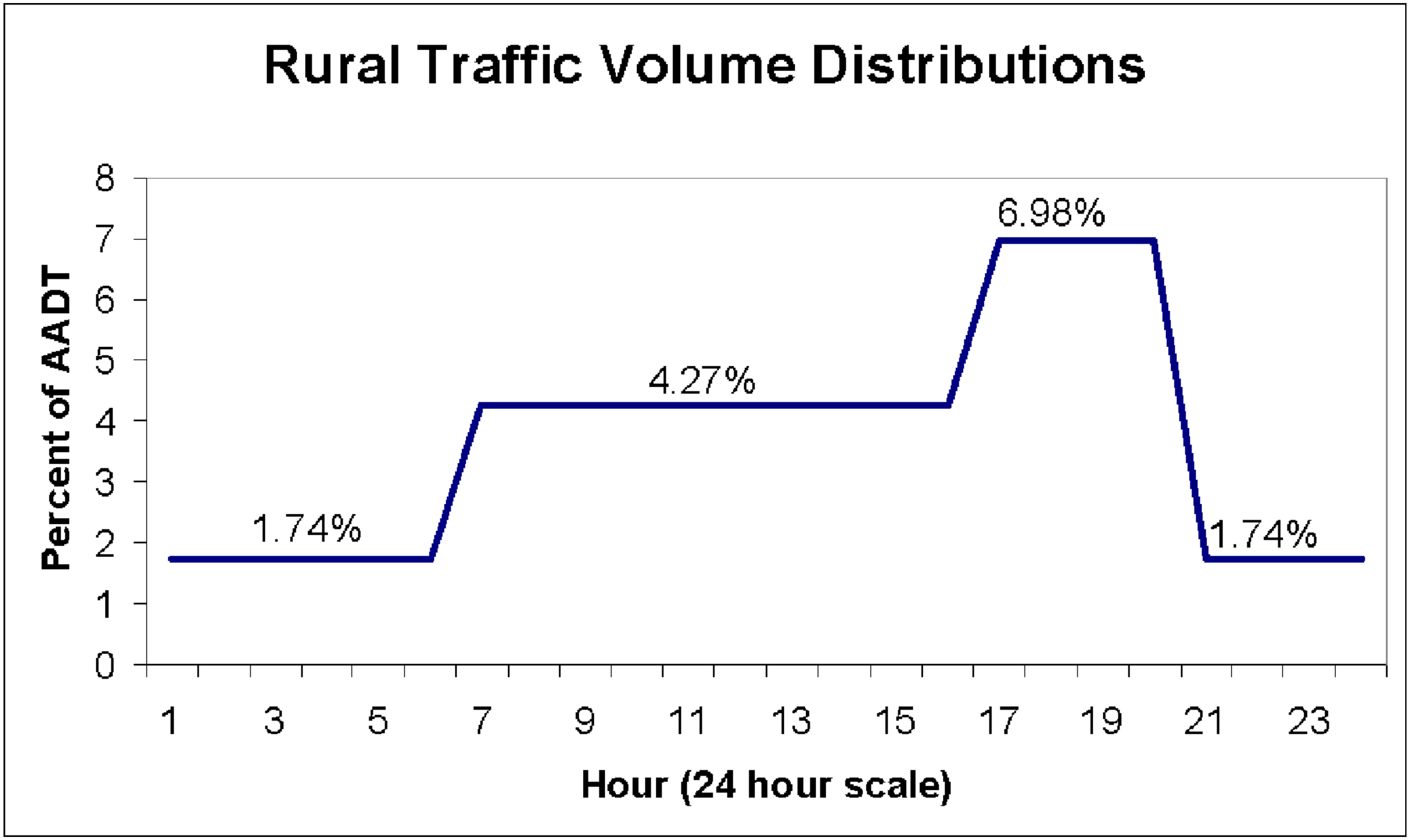


Figure 3.6 – Synthetic Rural Traffic Volume Divisions (*32*)

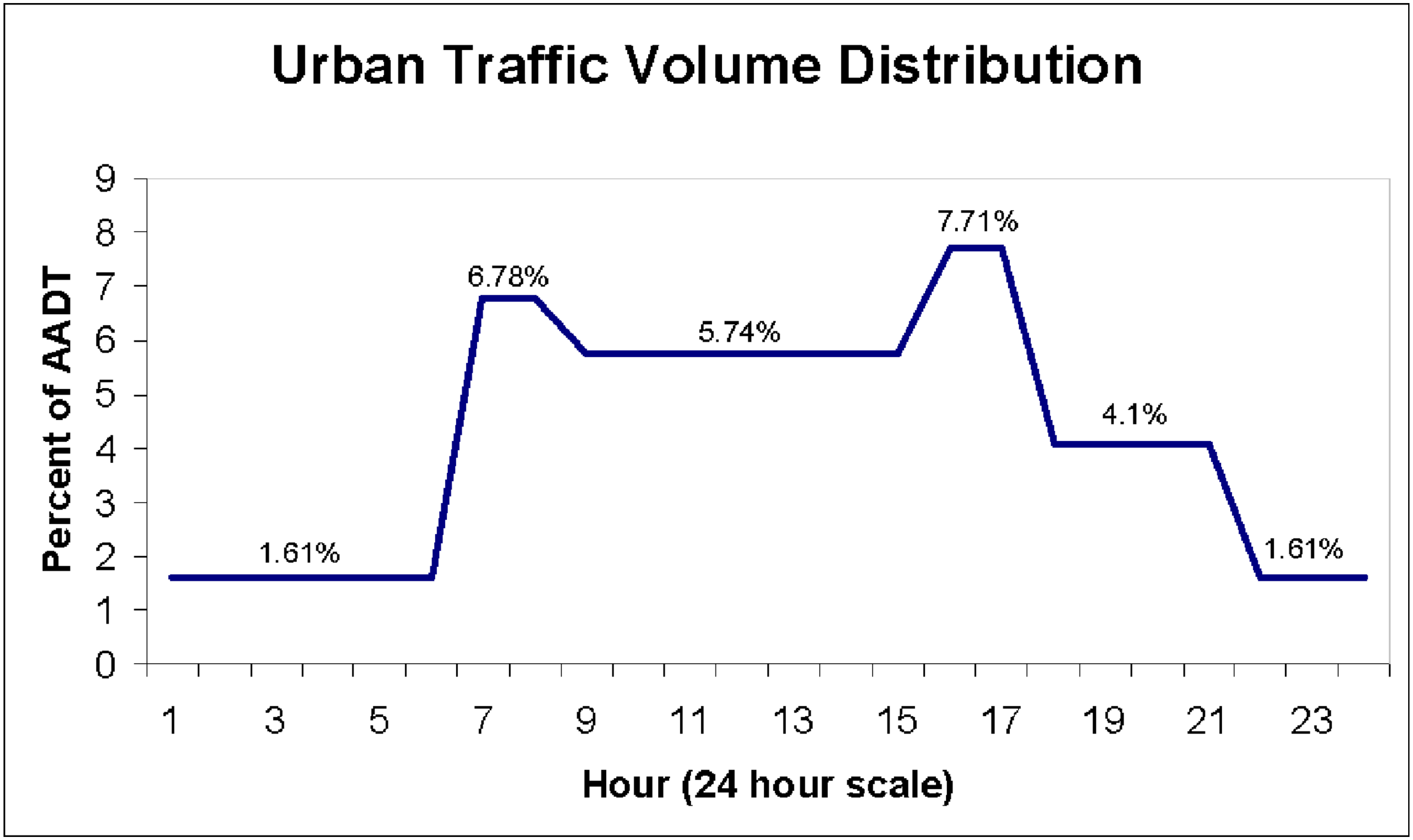


Figure 3.7 – Synthetic Urban Traffic Volume Divisions (*32*)

incident characteristics were used to allow for the representation of a variety of freeway facility and incident combinations. A summary of the experiments can be found in Table 3.1, with a complete discussion of these variables to follow.

Freeway facility variables are those variables that relate directly to the geometric and traffic operations aspects of the facility. This category included area type (rural or urban), number of lanes in a single direction (two to five), and normal demand volume to capacity (d/c) ratios (ranging from 0.5 to 0.9 in intervals of 0.1). An incident occurring on a facility with a v/c below 0.5 would most likely see little to no benefit in terms of delay savings even if an IMAP existed.

Table 3.1 – FREEVAL Experiments

Variable	Possible Values	Number of Levels
Area Type	Rural, Urban	2
Number of Lanes (per direction)	2, 3, 4, 5	4
Incident Severity*	Shoulder, 1 Lane Closure, 2 Lane Closure	3
Incident Duration	15, 30, 45, 60 minutes	4
Normal d / c Ratio	0.5, 0.6, 0.7, 0.8, 0.9	5
Total		**440 Combinations**

** 2 lane closures were not included for facilities with two lanes per direction*

Area type was simulated using two general templates for the simulations. The rural settings consisted of a 10 mile facility with a 75 mph free flow speed, assumed 10 percent trucks by volume, and interchanges occurring at every two miles and basic freeway segments in between. Interchanges were considered to be an off ramp and on ramp in succession, each 1500 feet in length, with acceleration or deceleration lanes of 500 feet and with 45 mph speed limits. Similarly, urban settings consisted of a 10 mile facility with a 70 mph free flow speed, assumed 5 percent trucks by volume, and the same interchange setup occurring every mile. It is important to note that FREEVAL requires that the study section begin and end with a basic freeway segment. Therefore, both the rural and urban sections used during the analysis began and ended with basic freeway sections.

FREEVAL does not allow for v/c ratios to be entered directly into the program. Instead, volumes are required for each segment within the freeway section to be analyzed. Therefore, the volumes entered into FREEVAL for the desired v/c ratio were determined using the capacity values determined by FREEVAL. These ideal capacity values were 2390 and 2330 per segment per lane for rural and urban segments respectively.

Table 3.2 – Percentage Capacity Remaining During Incidents (*30*)

Number of Freeway Lanes by Direction	Shoulder Disablement	Shoulder Accident	One Lane Blocked	Two Lanes Blocked	Three Lanes Blocked
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.26
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

Incident variables represent the characteristics of the incidents to be simulated and include the severity of the incident (shoulder, one lane, or two lanes blocked) and the duration of the incident (15, 30, 45, or 60 minutes). Incidents with more than two lanes blocked and incidents lasting in excess of an hour were not modeled because they are rare and represent major incidents which often require large, and sometimes specialized, clean-up efforts. Therefore, the benefits provided by IMAP are not expected to be significant for incidents of this magnitude. In addition, the case of an incident closing both lanes on a facility with only two lanes in each direction was not modeled due to the complete blockage of the freeway in a single direction. A capacity reduction factor was determined for each of the incident severities based on Exhibit 22-6 from the Highway Capacity Manual (*30*) duplicated in Table 3.2. The resulting value is a percent of the capacity remaining with the existing incident. The reduction factor for shoulder crashes was used for shoulder incidents because the reductions for shoulder disablements caused no impact in the simulations.

To extract the complete delay created by each of the incidents and to allow traffic to be restored to normal flow conditions after all incidents, all simulations were run for 1.5 hours. At the conclusion of the simulations, summary data were obtained for all simulations in the form of Vehicle Miles Traveled (VMT) Demand, VMT Volume (referred to as VMT Flow), and Vehicle Hours of Delay (VHD). Figure 3.8 shows a sample output from FREEVAL for a single simulation run. VMT Demand represents the vehicle miles that are expected to be traveled during the simulation assuming that all entering vehicles are able to exit the facility by the end of the simulation time. VMT Flow is the number of vehicle miles that are actually produced during the simulation time. VHD represents the amount of delay that is experienced collectively by the vehicles traveling through the facility during simulation. For runs when VMT Demand and VMT Flow are equal, all vehicles entering the facility are able to exit the facility during the simulation time and VHD represents the estimated total delay experienced by vehicles for the incident scenario. However, for some of the more severe

Title					
Number of ValidTime Intervals					
Period Duration (min)				**SECTION AND PERIOD TOTALS**	
SEGMENT NUMBER :	**14**	**15**	**16**		**units**
SECTION NUMBER :	14	15	16		
SECTION TITLE :	S14	S15	S16		
Length (ft)	1,500	1,500	3,780	10.00	mi
Number of lanes	2	2	2		
Type (B,W, ONR,OFR)	OFR	ONR	B		
Free flow speed (mph)	75	75	75		
Maximum d/c ratio**	0.50	0.50	1.43	**Oversaturated**	
Time Period Queueing Begins	1	1			
Mainline Vehicle-miles (Demand)	1010.4	1010.4	2546.3	35,566.7	VMT
Mainline Vehicle-miles (Volumes)	1010.4	1010.4	2546.3	35,566.7	VMT
Mainline Vehicle-hours Travel Time	40.0	44.9	58.5	649.9	VHT
System Vehicle-hours Delay	26.5	31.5	24.6	175.7	VHD
Mainline Speed (Ratio of VMT/VHT)	25.28	22.48	43.52	54.7	mph (veh)
Mainline Person-miles (Demand)	1212.5	1212.5	3055.5	42,680.1	VMT
Mainline Person-miles (Volumes)	1212.5	1212.5	3055.5	42,680.1	VMT
Mainline Person-hours Travel Time	48.0	53.9	70.2	779.9	PHT
Mainline Person-hours of Delay	31.8	37.8	29.5	210.8	PHD
Mainline Speed (Ratio of PMT/PHT)	25.3	22.5	43.5	54.7	mph (pass)
Average Mainline Travel Time (min)	0.67	0.76	0.99	11.0	min

Figure 3.8 – Example FREEVAL Output

incident scenarios, VMT Flow is less than VMT Demand. This suggests that at the end of the simulation time some of the vehicles that had entered the facility still had not exited the facility and were caught within the queue developed during the incident, which had not yet fully dissipated. This created a problem as some of the vehicle delay caused by the incident was not being captured at the end of the simulation time. To correct for this, a new field was created from the output data that was an adjusted VHD. This value was calculated by dividing the VHD output from FREEVAL by the VMT Flow to VMT Demand ratio. In doing this, the estimated total delay for the scenario can be determined for all of the simulation runs. Finally, the delay per VMT value for each simulation run was created by dividing the adjusted VHD by the VMT Flow. This value was then multiplied by 3600 to convert the value into units of seconds per VMT.

Delay Models

Once the data were collected for all of the simulation runs, all 440 data points were used to create regression models for the relationship of delay versus the incident d/c ratio. Incident d/c ratios for each experiment were calculated using Equation 3.1.

$$Incident\frac{d}{c} = \frac{VMT\ Flow}{Directional\ Number\ of\ Lanes * Ideal\ Capacity * Capacity\ \mathrm{Re}duction}$$

(Equation 3.1)

Where:

Ideal Capacity = 2390 vphpl for rural and 2330 vphpl for urban
Capacity Reduction = Capacity reduction factor from Table 3.2

To develop regression models, the data were grouped by area type, number of lanes per direction, incident duration, and incident severity. This resulted in each group containing five data points, one for each of the v/c variables. Each data point in the group was then plotted on a delay per VMT versus incident v/c grid. A best-fit line was then included to create a simple model for the given characteristics, resulting in 88 individual models. For simplicity, groups with like area type, number of lanes per direction, and incident duration were plotted on the same graph. An example graph with models for an eight-lane urban facility is shown in Figure 3.9. A summary of all of the models can be found in Table B.1 (rural) and Table B.2 (urban) in Appendix B, including the model equation, characteristics, R^2 value of the trend line, significance level for the regression parameter, and the standard error of the estimate. In addition, example graphs for each area type and number of lanes combination are included in Appendix B.

Single Incident Analysis

Single incident analysis estimates the benefits for a specific incident on a provided freeway facility assuming an IMAP program were installed. In other words, this analysis is simply an implementation of the FREEVAL delay models, expanded to estimate the expected delay for various incident durations and facility characteristics. The expected benefit (determined through single incident analysis) for a single incident is the estimated delay without an IMAP minus the estimated delay with an IMAP. A variety of incident variables are available and therefore many incident scenarios can be examined. The single incident methodology follows the single incident decision flow chart depicted in Figure 3.10.

Initially, several input values are required that are related to the facility and incident that is to be analyzed. Facility data are pulled from the Facility Characteristics component of the Data section of the methodology. Incident values that are needed are the time period in which the incident occurred, incident severity, incident duration, and the estimated reduction of incident duration if an IMAP service was added (as a percentage). During annual analysis, the time period in which the incidents occur and incident severities are determined by the incident distribution tree found in Figure 3.3. Incident duration is based on the clearance time of the incident and the response time of responding vehicles while the estimated reduction of the duration due to IMAP is figured as the percentage difference between the durations with an IMAP vehicle and a non-IMAP vehicles responding. The determination of incident duration and the reduction of duration due to IMAP are discussed in more detail below.

Incident Duration and Clearance Time

To account for the varying response times (with and without IMAP) for the scenarios, a breakdown of the total incident duration into response time and clearance time is needed. While the response time for incidents depends on the presence of an IMAP program, clearance time is expected to be independent of it. Instead, clearance time is related to the type of incident and should not differ significantly for incidents with and without IMAP (*27*). To determine a clearance time for the given incident duration, incident response and clearance durations from a recent Massachusetts study (*12*) were used to determine a total duration percentage breakdown of clearance times for the respective incident types. Table 3.3 displays the various durations, as well as the percentage breakdowns for clearance times, from the Massachusetts study for incidents with an IMAP program. Vehicle disablement and accident on lane were applied to shoulder and lane (one lane and two or more lane) incidents, respectively. These clearance time percentages (taken to be 0.67 for all incidents) were then applied to the incident durations from the incident distribution tree, resulting in clearance time estimations for the given incidents as shown in Table 3.4.

Table 3.3 – Incident Response and Clearance Attributes (*12*)

Incident Type	Location	Response and Detection Time (min)	Clearance Time (min)	Total Time (min)	Clearance %
Vehicle Disablement	Shoulder	10	20	30	67
Accident on Lane Moved to Shoulder	Shoulder / Lane	10	20	30	67
Accident on Lane	Lane	10	25	35	71

Table 3.4 – Duration and Clearance Times by Incident Type

Incident Type	Peak Duration (min)	Off-Peak Duration (min)	Peak Clearance Time (min)	Off-Peak Clearance Time (min)
Shoulder	15	15	10.05	10.05
1 Lane Blocked	31	41	20.77	27.47
2+ Lanes Blocked	51	94	34.17	62.98

In addition to clearance times, response times for incidents also must be determined. However, unlike clearance times, response times are not dependent on incident type and are expected to be consistent for all incidents that an IMAP responds to. Therefore, the response time is determined for two cases: with an IMAP program and without.

Response Time Models

For the case of an IMAP present on the facility, models were developed to determine the average response distance for randomly occurring (over time and space) incidents. Simple simulations were run to examine the relationship between facility average turnaround point spacing (referred hereafter as turnaround spacing) and IMAP vehicle response distance. The

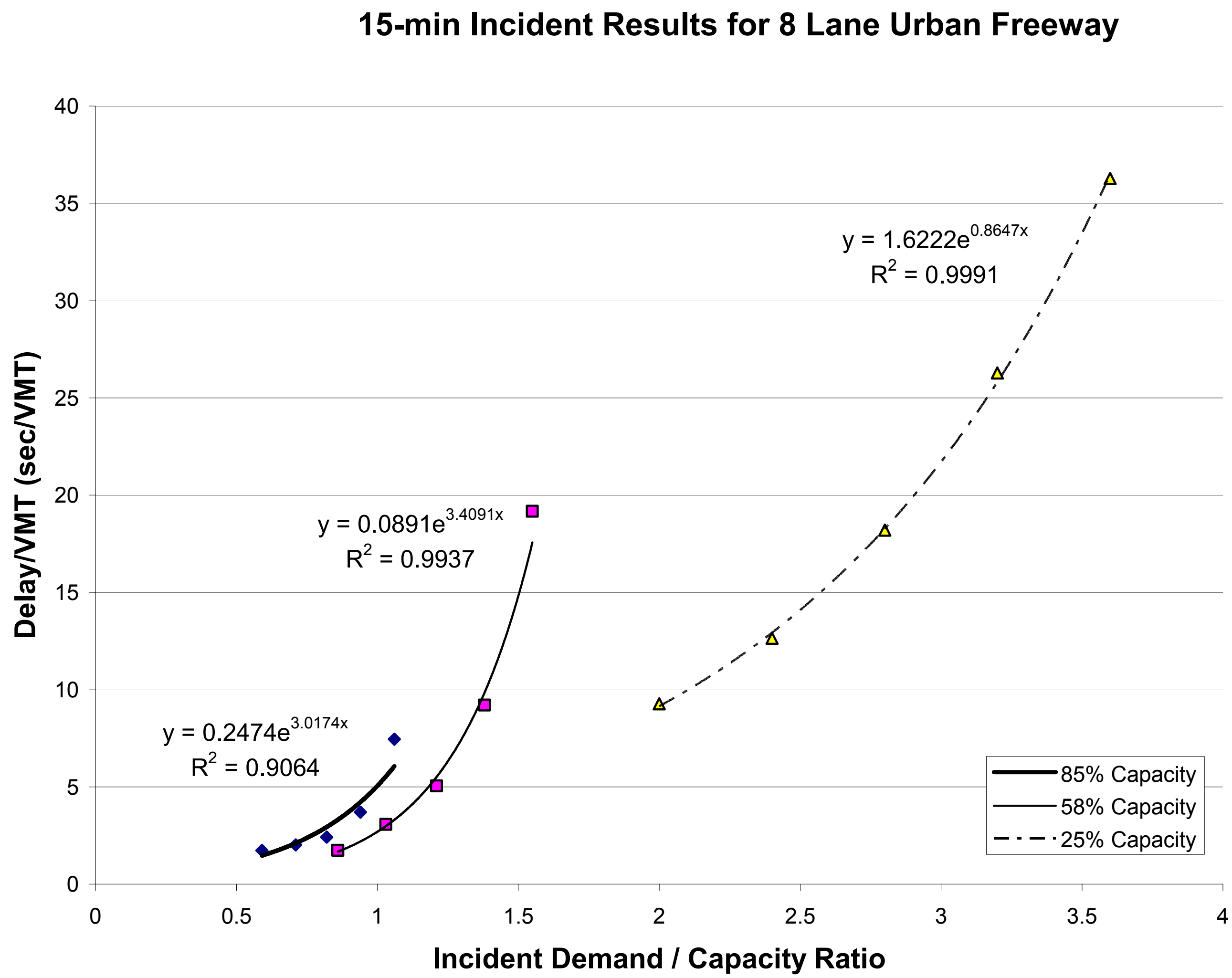


Figure 3.9 –Urban Facility Delay Rate Models for 8 Lane and Indicated Available % Capacities

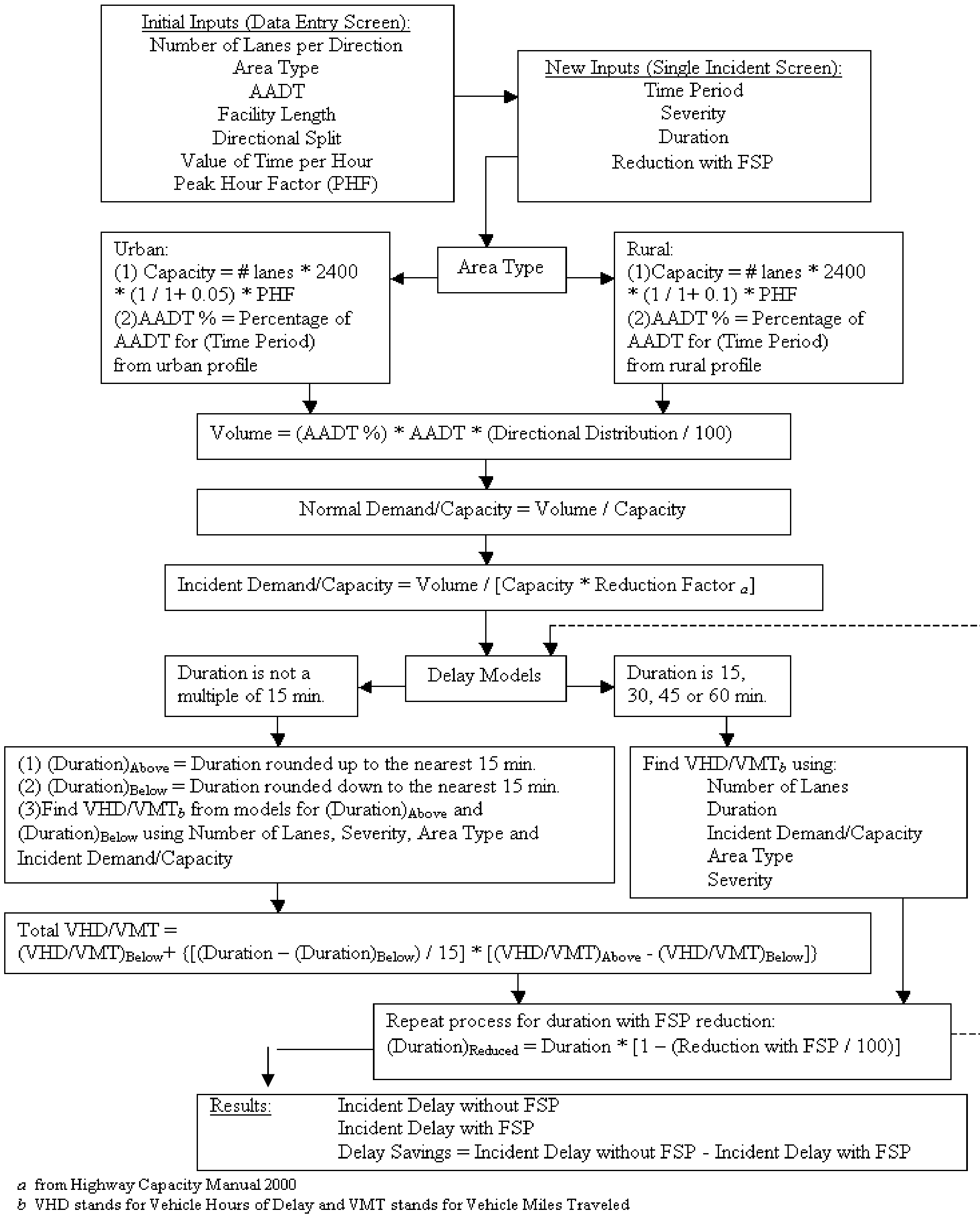


Figure 3.10 – Single-Incident Decision Flowchart

freeway facility is divided into a number of cells that represent directional segments occurring between turnaround points on the facility, with the length of each cell being equal to the average turnaround spacing for the facility. The average turnaround spacing for the facility is the average distance between points on the facility at which an IMAP vehicle can turn around (i.e. interchanges, median openings, etc) in miles. Therefore, the overall length of the facility is treated as a multiple of the average facility turnaround spacing. For example, a facility with an average turnaround spacing of two miles and an overall length of 14 is modeled as having seven average turnaround spacings. The simulation for this facility would include 14 cells, seven for each direction. A generalized display of this concept can be seen in Figure 3.11.

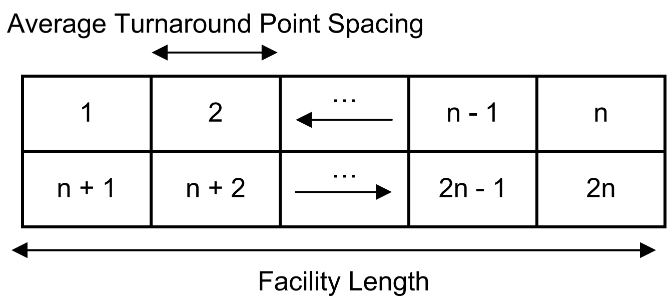


Figure 3.11 – Generalized Freeway Facility Representation

In order to create generalized models for freeway facilities, simulations were run for a variety of scenarios. These included facilities ranging in length from five to 15 cells. The main objective of these simulations was to determine the average response time of an IMAP vehicle to an incident occurring anywhere on the facility. This means that the average response time for the IMAP vehicle must take into account the incident occurring within any cell during the simulation. In addition, because the IMAP vehicle is assumed to be roaming, the IMAP vehicle could also be in any cell within the facility. Finally, the number of IMAP vehicles roaming on the facility was varied from one to four vehicles. It is possible that an IMAP program may have more than four vehicles roaming on a site, but this would be outside the scope of the models. Therefore, the model for four IMAP vehicles roaming is used for cases of the number of IMAP vehicles roaming is equal to or greater than four. This is expected to give a slightly conservative estimate of response time. A summary of the parameters for these simulation experiments can be found in Table 3.5.

Table 3.5 – Response Time Simulation Experiment Variables

Parameter	**Possible Values**
Number of Cells per Direction	5 to 15
Number of IMAP Vehicles	1 to 4
Incident Location	10 to 30 (twice the number of cells per direction)

Numerical simulations (in Excel) were completed by incrementing the location of the incident from cell 1 to cell n in one direction (where n is the number of cells per direction) and from cell n + 1 to 2n in the opposite direction. For each increment of the incident location, the location of the IMAP vehicle was incremented from cell 1 to cell 2n. During all iterations, incidents and vehicles are assumed to be in the center of the cell to which they are assigned. The distance from the IMAP vehicle to the incident was then calculated by counting the number of cells between the two. This distance is simply the number of cells between the vehicle and incident location when the incident is downstream of the vehicle; this could increase when accounting for directional restrictions of the facility. For example, in Figure 3.11, a vehicle in cell 2 responding to an incident in cell 1 would travel a distance equivalent to one cell. However, a vehicle in cell 1 responding to an incident in cell 2 would have to travel a distance of three cells due to the need for the IMAP vehicle to turn around. This process was completed for the number of cells per direction ranging from five to 15 to complete the single vehicle simulations. The entire process was repeated assuming two, three, and four IMAP vehicles roaming on the facility. For these scenarios, all combinations of incident and vehicle locations were included with no preference as to the responding vehicle. In other words, the IMAP vehicle with the shortest distance was assumed to be the responding vehicle. Summary information of the results of the response distance simulations is shown in Table C.2.

Once these simulations were completed, data for the average response distance versus facility length were plotted, with both scales given in the number of turnaround spacings. This means that both scales depend on the average distance between turnaround points as discussed above. In addition, different plots are given based on the number of IMAP vehicles roaming the site. Regression models developed from these plots are shown in Figure 3.12, including the model equation and R^2 value for each model. Each of the models require facility length (as a function of the average turnaround spacing for the facility), which can be found by simply dividing the overall length of the facility by the facility average turnaround point spacing. The output of these models is then the average response distance, also as a factor of the average turnaround spacing for the facility. This response distance can then be converted to miles by multiplying the output of the model by the average turnaround spacing for the facility. Once the average response distance is known, the average response time is determined by dividing the distance by the average speed of the IMAP vehicle (assumed to be the free flow speed during off-peak incidents and one-half of the free flow speed for incidents occurring during peak hours). This results in the estimated average response times for IMAP vehicles during peak and off-peak hours. A numerical application of these models can be seen in the following section.

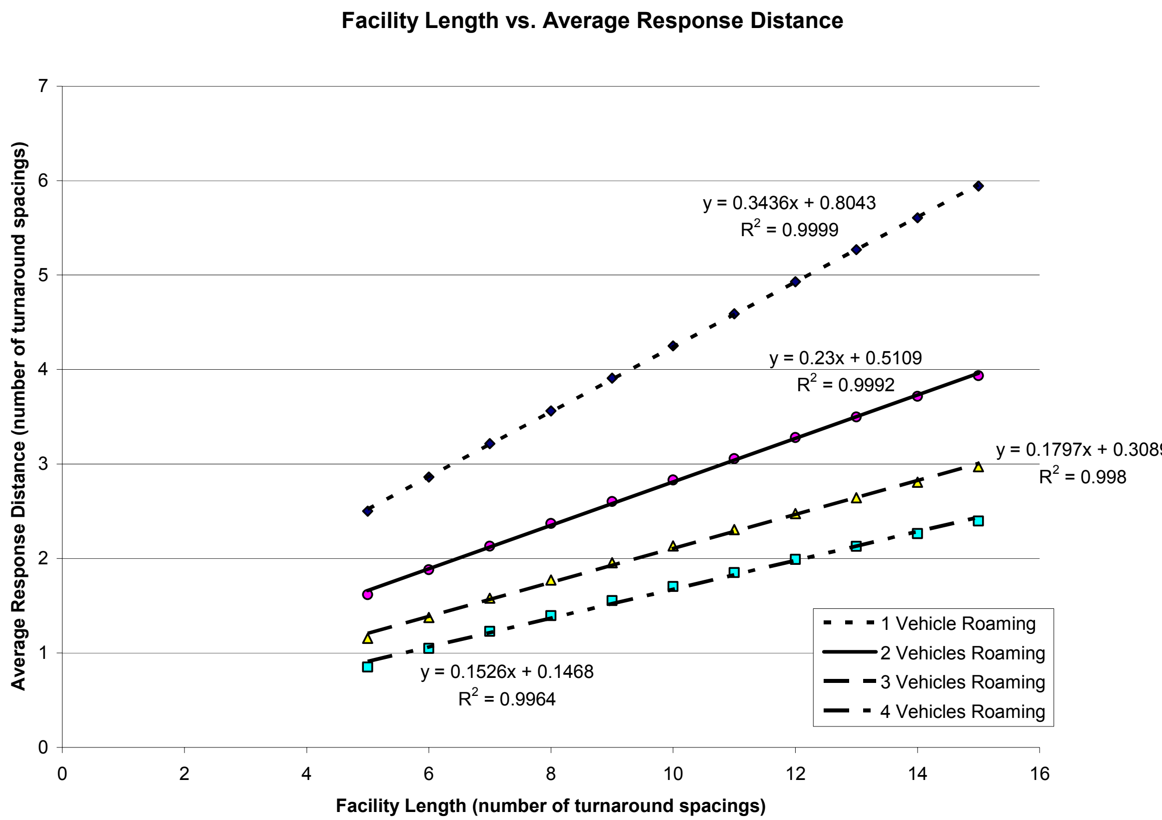


Figure 3.12 – Average Response Distance Estimation Models

Response times without an IMAP program at the facility are simply the supplied response time without IMAP found in the Facility Data component of the Data section. This constant response time without IMAP is the estimated time it takes for a non-IMAP vehicle (such as a police vehicle or tow truck) to reach the incident site.

IMAP Response Time Example Application

As an example application of the IMAP response time models, consider a twelve mile urban freeway facility with a turnaround spacing of 1.5 miles and three IMAP vehicles roaming. This would result in an equivalent facility length of eight interchange spacings as shown in Equation 3.2.

$$Equivalent\ Facility\ Length = \frac{Facility\ Length(miles)}{Turnaround\ Spacing(miles)} = \frac{12}{1.5} = 8 \qquad \text{(Equation 3.2)}$$

Equation 3.3 (from Figure 3.12) is used to estimate the average response distance for this example with three IMAP vehicles roaming and results in a calculated average response distance of 1.7465 miles.

$$Avg.\ \mathrm{Re}\,sponse\ Dis\tan ce = 0.1797(x) + 0.3089 = 0.1797(8) + 0.3089 = 1.7465\ miles$$
(Equation 3.3)

Finally, the response time for incidents is calculated using assumed average IMAP vehicle speeds of 35 mph and 70 mph for urban peak and off-peak incidents, respectively. The calculation of response times (RT), in minutes, is shown in Equations 3.4 and 3.5.

$$\text{Off} - \text{Peak RT(min)} = 60\left(\frac{\min}{hr}\right) * \frac{Avg.\ \mathrm{Re}\,sponse\ Dis\tan ce(miles)}{Avg.\ IMAP\ Veh.\ Speed(mph)} = 60 * \frac{1.7465}{70} = 1.5\ \min$$
(Equation 3.4)

$$Peak\ RT(\min) = 60\left(\frac{\min}{hr}\right) * \frac{Avg.\ \mathrm{Re}\,sponse\ Dis\tan ce(miles)}{Avg.\ IMAP\ Veh.\ Speed(mph)} = 60 * \frac{1.7465}{35} = 3.0\ \min$$
(Equation 3.5)

Traffic Characteristics Computations

Once the required values are acquired, the analysis (see Figure 3.10) begins by determining the capacity of the facility and volume (as a percent of the AADT) based on the area type. Capacity is calculated according to Equation 3.6.

$$Capacity = DirectionalNumberofLanes * BaseCap * \frac{1}{(1 + Truck\%)} * PHF \quad \text{(Equation 3.6)}$$

Where:

BaseCap = 2400 for rural sites or 2300 for urban sites
Truck% = 10 percent for rural or 5 percent for urban (as a decimal)

Volume during the time of the incident is then determined by the time period in which the incident occurs and the AADT percentage that is determined using the volume profiles found in Figure 3.6 or 3.7, depending on the area type. Peak and off-peak percentages were calculated as the average of all percentages falling into the respective category. For example, the peak percentage was the average of the 7 to 9 am percentage and the 4 to 6 pm percentage for the respective area type. After the AADT percentage has been determined volume, demand to capacity ratio, and incident demand to capacity calculations are computed. Volume is simply calculated according to Equation 3.7.

$$Volume = AADT\ Percentage * AADT * \frac{Directional\ Distribution}{100} \quad \text{(Equation 3.7)}$$

The normal demand to capacity ratio is then simply figured as the volume divided by the capacity. Finally, the incident demand to capacity ratio is calculated using Equation 3.8.

$$Incident\frac{d}{c} = \frac{Volume}{Capacity*Capacity\ Adjustment\ Factor} \qquad \text{(Equation 3.8)}$$

Where:

Capacity Adjustment Factor = Capacity adjustment factor from Table 3.2

Delay Model Utilization

The next step is to determine the delay caused by the incident without and with an IMAP program present at the facility. If the duration of the incident is a multiple of 15 minutes (e.g., 15, 30, 45, or 60 minutes), then the number of lanes, incident duration, incident demand to capacity ratio, facility area type, and the incident severity are used to select the appropriate delay model from Table B.1 or B.2. The delay, in units of seconds/VMT, is simply the output of the selected model with the incident demand to capacity ratio as the input.

However, if the duration is not a multiple of 15 minutes, interpolation between models is required. The variables $Duration_{Above}$ and $Duration_{Below}$ are defined as the duration rounded up to the nearest 15 minute value and rounded down to the nearest 15 minute value respectively. For example, for an incident duration of 20 minutes, $Duration_{Above}$ and $Duration_{Below}$ would be equal to 30 minutes and 15 minutes respectively. Delay estimations (represented as $(VHD/VMT)_{Above}$ and $(VHD/VMT)_{Below}$) are then determined for $Duration_{Above}$ and $Duration_{Below}$ in the same manner as if the duration had been a multiple of 15 minutes. In order to calculate the delay for the actual duration from these values, the Equation 3.9 is used.

$$Total\frac{\sec}{VMT}=\left(\frac{\sec}{VMT}\right)_{Below}+\frac{Duration-Duration_{Below}}{15}*\left[\left(\frac{\sec}{VMT}\right)_{Above}-\left(\frac{\sec}{VMT}\right)_{Below}\right]$$

(Equation 3.9)

A special case of this procedure is necessary when the incident duration is in excess of 60 minutes. No models were developed for durations greater than 60 minutes and therefore a type of extrapolation of the models is needed to estimate delay for incidents of this magnitude. Equation 3.10 is used to calculate the estimated delay for incidents with a duration of this magnitude and applies the estimated delays at 45 and 60 minutes.

$$Total\frac{\sec}{VMT}=\left(\frac{\sec}{VMT}\right)_{60}+\frac{\left[\left(\frac{\sec}{VMT}\right)_{60}-\left(\frac{\sec}{VMT}\right)_{45}\right]*(Duration-60)}{15} \qquad \text{(Equation 3.10)}$$

The delay estimation process is repeated for the reduced duration assuming an IMAP program being added. To do this, the duration is adjusted to reflect the reduced duration due to reduced response time. Results of the single incident analysis include the incident delay without IMAP, incident delay with an IMAP program present, and the delay savings (calculated as the delay without IMAP minus the delay with IMAP present).

Cost Calculations

After the Delay Estimates component is completed, the annual cost of implementing an IMAP is calculated by the IMAP Costs component. To determine the annual costs of an IMAP program, data are required from the IMAP Characteristics and Facility Characteristics portions of the Data section in addition to calculating the number of IMAP vehicles that will roam the facility during operating hours. The number of IMAP vehicles to be used on the facility can either be estimated based on current IMAP coverage used throughout North Carolina or simply supplied as an input if the estimated number of vehicles does not agree with the desired level of coverage. While not included in this research, queuing theory could also be used to estimate the percentage of time that an IMAP is available to respond to incidents. Current IMAP coverage in North Carolina was estimated from a regression model using the number of vehicles as the dependent variable and route length and AADT as independent variables (*32*). Data points were identified using route length and AADT data provided for current IMAP installations throughout the state. The model predicts that IMAP facilities that service heavier traffic over extended distances will require the use of more vehicles as expected. Figure 3.13 displays the model. However, Figure 3.13 is a fleet size estimation, not an estimation of the number of vehicles that should be roaming on the site. On average for North Carolina IMAPs, the number of roaming IMAP vehicles is equal to one-half of the fleet size rounded up to the nearest whole vehicle. Therefore, the number of roaming vehicles is estimated to be one-half of the fleet size estimated from Figure 3.13.

Once the required values are determined, annual cost figures can be determined according to Equation 3.11.

$$\text{Annual Costs} = \text{Number of Veh} * \text{Number of Days} * \text{Hours per Day} * \text{Cost per Hour}$$

(Equation 3.11)

Where:

Number of Veh = Number of IMAP vehicles roaming on the facility

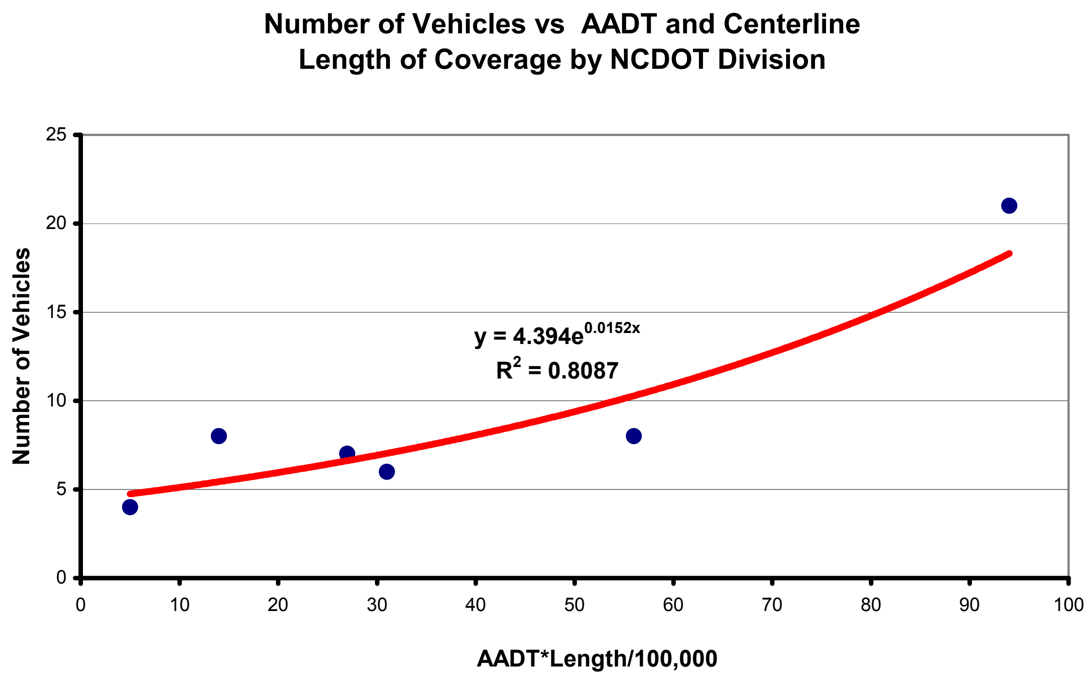


Figure 3.13 – Fleet Size Estimation: Regression Model (*32*)

The final component of the Operational Level section of the methodology is B/C Ratio. This component estimates an annual benefit to cost ratio assuming an IMAP is provided on the given facility. Benefits are calculated using the Delay Estimates and IMAP Costs components of the Operational Level section of the methodology. Simply, the annual incident delay savings is the incident delay savings per unique incident type (see Figure 3.3) multiplied by the number of annual incidents of that specific type summed over all incident types. The incident delay savings for each incident type is calculated using the same methodology used for the single incident analysis (shown in Figure 3.10) in the Delay Estimates step. Finally, the annual value of delay savings for all incidents is multiplied by the value of time, in dollars per hour, to convert the delay savings into an annual monetary savings. This value is then divided by the annual costs calculated by the IMAP Costs step to give an annual B/C ratio.

CHAPTER 4 – APPLICATION AND RESULTS

The application of the methodology that was developed to existing IMAP sites as well as potential IMAP sites is presented in this chapter. Planning and operational analyses for both groups were completed and the results discussed in the following sections.

4.1 Application of Results – Existing Sites

A goal of this thesis is to apply the methodology to existing IMAP sites in North Carolina. Currently, North Carolina Department of Transportation has deployed IMAP services in five Divisions, including 16 individual routes, across the state. Facility data for each of these routes are given in Table 4.1 (*32*). With these data, planning and operational analyses for each of the facilities were carried out.

Planning Level Analysis

Table 4.2 displays the results of the planning level analysis (*32*) when contrasted to all freeway sites statewide. The elevated values found in Table 4.2 show that, on average, the IMAP programs are deployed on facilities with the greatest need. For example, Interstate 40 in division five ranks in the 70th percentile for crashes per 100 MVM, indicating that only 30% of the roadway facilities in the state rank higher. However, Interstate 40 facility in Haywood County is an exception to the general trend. The IMAP program installed on this facility does not rank among the upper percentiles for the various measures (i.e. 15th percentile for AADT per lane, etc.), yet the facility still has an IMAP

Table 4.1 – Planning Analysis Data for Existing IMAP Sites (*32*)

Division	Location	Operating Hours	Length (Miles)	AADT	No. Lanes	Crashes per Year
5	I-40 Triangle	6 am to 8:30 pm M-F	28	89000	6	971
5	I-85 Triangle	6 am to 8:30 pm M-F	16	70800	4	402
7	I-40 Greensboro	5 am to 10 pm M-F	14	87000	4	534
7	I-85 Greensboro	5 am to 10 pm M-F	5	58000	6	103
7	I-40 and I-85 Greensboro	5 am to 10 pm M-F	39	87000	8	880
9	US 52 Winston-Salem	5:30 am to 9 pm M-F	18	47000	4	394
9	US 421 Winston-Salem	5:30 am to 9 pm M-F	3	49000	4	50
9	I-40 Winston-Salem	5:30 am to 9 pm M-F	23	65000	6	317
9	I-40 Business Winston-Salem	5:30 am to 9 pm M-F	10	56000	4	239
10	I-85 Charlotte	5:30 am to 9:30 pm M-F and 10 am to 6 pm Sat and Sun	55	80000	6	1361
10	I-77 Charlotte	5:30 am to 9:30 pm M-F and 10 am to 6 pm Sat and Sun	30	100000	6	1159
10	I-277 Charlotte	5:30 am to 9:30 pm M-F and 10 am to 6 pm Sat and Sun	5	72000	6	250
10	I-485 Charlotte	5:30 am to 9:30 pm M-F and 10 am to 6 pm Sat and Sun	**	**	**	**
12	I-40 Statesville	5:30 am to 9 pm M-F	33	48000	4	400
12	I-77 Statesville	5:30 am to 9 pm M-F	24	48000	4	272
14	I-40 Haywood County	24 hours a day, 7 days a week	20	24000	2	100

** Denotes No Data

Table 4.2 – Planning Analysis Results for Existing IMAP Sites- All Sites (*32*)

Division	**Location**	**Crashes per 100 MVM** (% rank for all sites)	**Crashes per Mile per Year** (% rank for all sites)	**AADT per Lane** (% rank for all sites)
5	I-40 Triangle	70	80	90
5	I-85 Triangle	70	75	95
7	I-40 Greensboro	75	85	95
7	I-85 Greensboro	70	75	65
7	I-40 and I-85 Greensboro	55	75	75
9	US 52 Winston-Salem	75	75	80
9	US 421 Winston-Salem	65	70	80
9	I-40 Winston-Salem	50	65	75
9	I-40 Bus. Winston-Salem	75	75	90
10	I-85 Charlotte	65	75	85
10	I-77 Charlotte	70	85	95
10	I-277 Charlotte	85	85	80
10	I-485 Charlotte	**	**	**
12	I-40 Statesville	55	60	80
12	I-77 Statesville	50	60	80
14	I-40 Haywood	45	35	15

** Denotes No Data

program. This is due to the mountainous terrain and rural setting of this site. Incidents that occur along this stretch of Interstate 40 have the potential to be very severe or have very long durations. Therefore, an IMAP was installed to help offset these possibilities and aid drivers involved in these extreme cases. Additionally it must be noted that the data used for this thesis were from the late 1990's, at which time no data were available for Interstate 485.

Operational Level Analysis

Using the data shown in Table 4.1, an assumed turnaround spacing of 1 mile (urban) or 3 miles (rural), and a value of time of $10 per hour, operational analyses of existing IMAP sites were conducted. Because the sites in Table 4.1 currently have patrols, cost information is readily available and can be found in Table 4.3. However, the costs are broken down by division, not individual facilities. Thus, the average cost for an individual facility was estimated to be the average cost per vehicle per hour for the division. The average hourly costs of IMAP vehicles, shown in Table 4.3, are small because of NCDOT policies regarding IMAP vehicles. NCDOT does not purchase the vehicles; vehicles are rented them from another department within NCDOT. In addition, most Divisions use storage facilities owned by other departments, eliminating the need to purchase additional storage for IMAP vehicles. Therefore, the majority of hourly IMAP vehicle costs include only driver salary, vehicle rent, and minimal administrative costs.

The operational analyses of existing IMAP sites are summarized in Table 4.4. These results indicate that, statewide, the current IMAP programs are economically justified (i.e. benefits exceed costs). It is important to note that while the Interstate 40 facility in Haywood County has no measurable benefits in terms of delay savings, there are other significant unquantified benefits such as motorist safety, security, and service.

4.2 Application of Results – Candidate Sites

An essential step in this project is the application of the methodology to candidate IMAP sites in North Carolina. The chosen candidate sites were selected through GIS analysis of freeway sites in North Carolina. Planning and operational level analyses then followed for each of the candidate sites.

Candidate Site Selection

One of the benefits of the methodology developed in this thesis is the ability to compare the merits of candidate IMAP sites in North Carolina. However, in order to do so, possible candidate sites must first be identified. For this thesis, this was accomplished through the use of GIS. First, the three index statistics (AADT per lane, crashes per mile per year, and crashes per 100 MVM) were calculated for each freeway segment. Next, a field was created in the crash segment file indicating whether or not it is covered by an IMAP. The data were then analyzed to calculate the percentile distributions of the three index statistics for three categories of facilities: 1) all segments, 2) segments covered by IMAP, and 3) segments not

Table 4.3 – IMAP Hourly Costs by NCDOT Division

Division	Total Annual Cost	Total Hours Patrolled Annually	Total Trucks	Hourly Cost per Truck
5	$436,900	3600	7	$17.30
7	$436,700	3840	8	$14.20
9	$610,600	3600	8	$21.20
10	$1,762,700	4608	21	$18.20
12	$379,000	4608	6	$13.70
14	$285,700	8640	4	$8.30
			Average Hourly Cost per Truck	**$15.50**
			Weighted Average Cost[a]	**$16.70**

a Averages are weighted by multiplying the hourly costs times the total trucks for each division, summing the values for all divisions, and dividing by the total number of vehicles

Table 4.4 – Operational Level Analysis Summary for Existing IMAP Sites in North Carolina

Division	Location	Total Annual Delay Savings (VHD)	Total Annual Costs	Benefit / Cost *
14	I-40 Haywood County	200	$262,800	0.00
12	I-40 Statesville	30,400	$154,100	1.97
12	I-77 Statesville	18,500	$154,100	1.20
10	I-85 Charlotte	245,200	$432,300	5.67
10	I-77 Charlotte	519,700	$345,800	15.03
10	I-277 Charlotte	6,000	$259,400	0.23
10	I-485	No Data	No Data	No Data
9	US 52 Winston-Salem	29,900	$238,500	1.25
9	US 421 Winston-Salem	900	$238,500	0.04
9	I-40 Winston-Salem	18,500	$238,500	0.78
9	I-40 Business Winston-Salem	23,600	$159,800	1.48
7	I-40 Greensboro	391,700	$181,100	21.63
7	I-85 Greensboro	1,100	$181,100	0.06
7	I-40 and I-85 Greensboro	45,000	$241,400	1.86
5	I-40 Triangle	245,700	$259,500	9.47
5	I-85 Triangle	219,300	$194,600	11.27
	Statewide Totals	**1,795,700**	**3,541,500**	**5.07**

* Assuming $10/hour value of time

covered by IMAP. Existing IMAP facilities were then manually located on a map using the beginning and ending mileposts of the patrols. The resulting IMAP location map can be viewed along with selected features of the incident segment file. By displaying current IMAP locations and the 85th percentile for any of the three index statistics, it is possible to obtain a general idea of where high-impact areas are located. Figure 4.1 shows that IMAP programs are located at high-impact locations. However, the map that shows all three index statistics is disjointed because index values for contiguous facilities can vary substantially. In addition, for very short segments, the crashes per mile per year and crashes per 100 MVM values are inflated because the formulas divide by facility length. To account for this inflation and the scattering of values, density maps were created using the three index statistics. Density maps spread values for the line segments over a wider area, showing concentrations more clearly and eliminating or reducing any disconnect between adjacent segments. Figures 4.2, 4.3 and 4.4 show the density maps for 85th percentile or higher calculations for AADT per lane, crashes per mile per year and crashes per 100 MVM, respectively. The combination of the density maps in Figure 4.5 shows continuous segments where IMAP service may be needed by displaying the 85th percentile and above for the three indices along with existing IMAP service. Two important observations can be made from the map. First, existing IMAP programs are located in high-impact locations. Second, I-440 in Raleigh and the interstates around Asheville appear to be prime candidates for IMAP expansion.

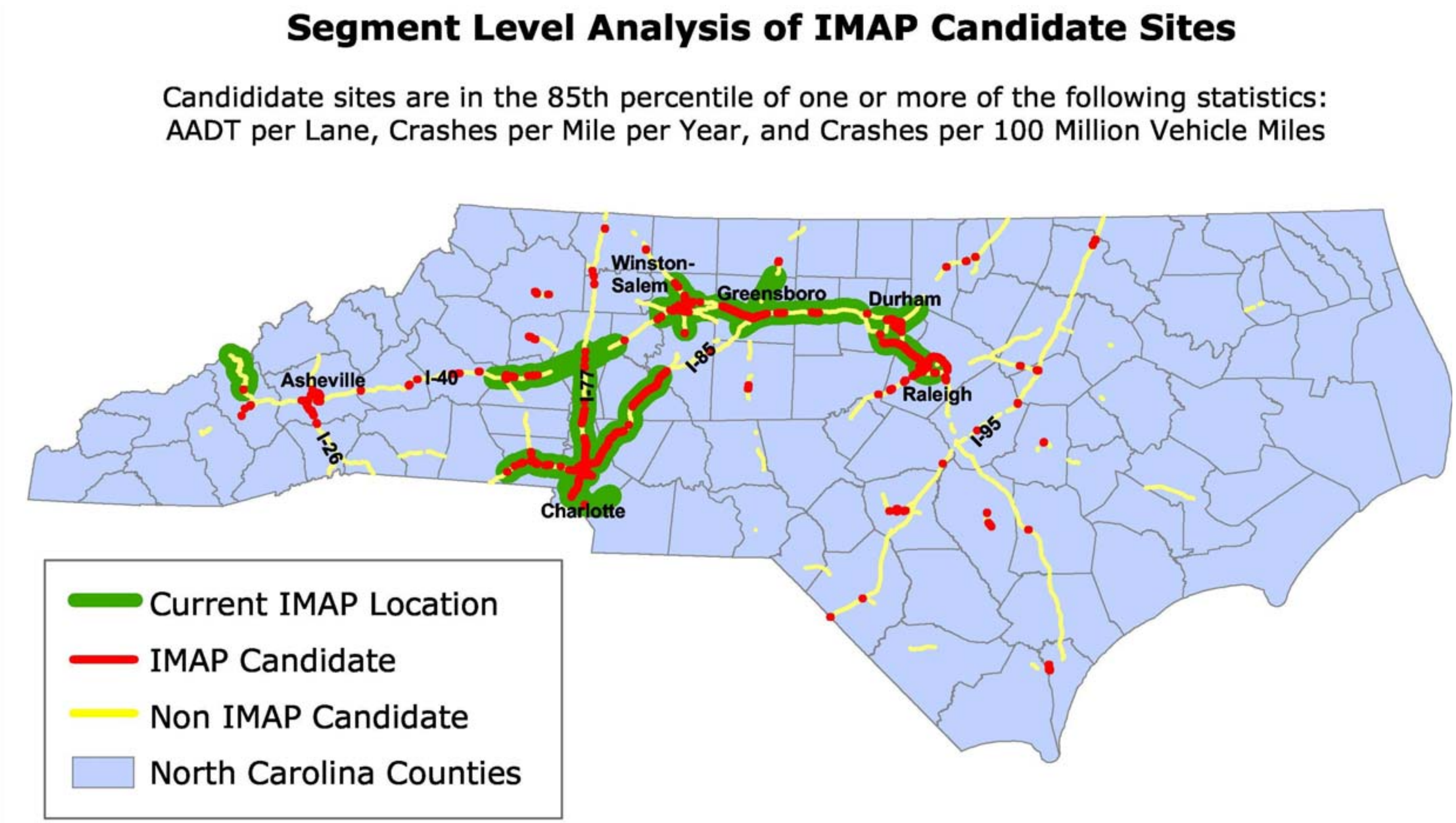


Figure 4.1 – Segment Level Planning Analysis (*32*)

Presented below are the evaluation results for two candidate sites in North Carolina, Asheville and Raleigh, identified through GIS analysis as the most viable candidates for future IMAP sites (*32*). Table 4.5 displays the facility data for each of the candidate sites obtained from Khattak et al (*28*), as well as other estimated facility data. The number of roaming vehicles was estimated for each site using one-half of the fleet size suggested by Figure 3.12 (rounded up) and the average distance between turnaround points was estimated using knowledge of the area.

Table 4.5 – Candidate Site Facility Data

Variable	**Raleigh**	**Asheville**
Facility Length	10.44 miles	15.23 miles
AADT	82,038	63,887
Annual Total Crashes	712	303
Area Type	Urban	Urban
Number of Lanes per Direction	3	2
Directional Distribution	60 / 40	60 / 40
PHF *	*0.9*	*0.9*
Value of Time *	*$15 per hour*	*$10 per hour*
Number of Roaming Vehicles *	*3*	*3*
Average Distance Between Turnaround Points *	*1 mile*	*2 miles*
Average Response Time Without IMAP *	*20 minutes*	*20 minutes*
Hours of Operation per Day *	*15*	*15*
Annual Days of Operation *	*250*	*250*

*Note: * represents estimated values not included in Khattak et al (28)*

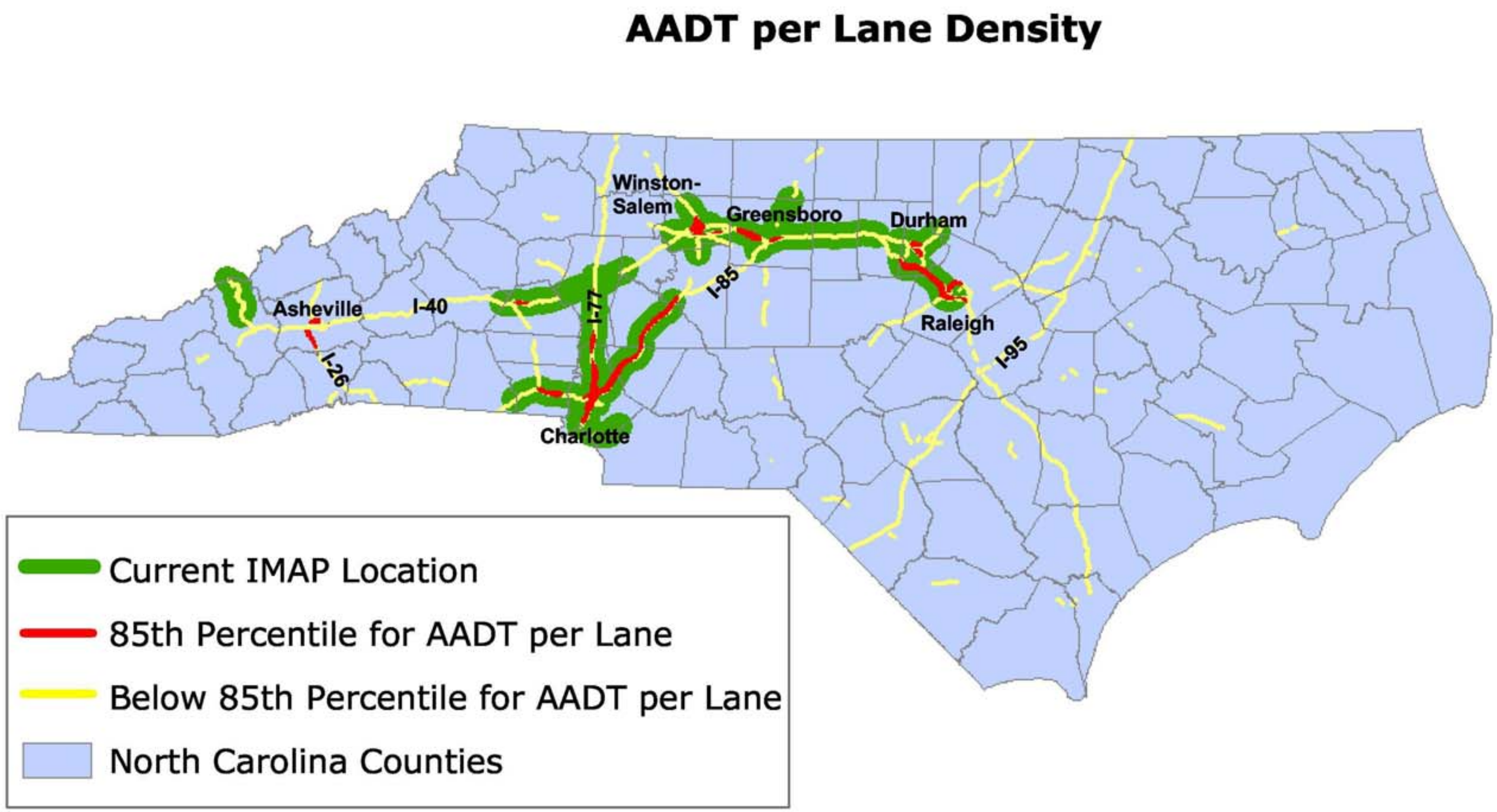


Figure 4.2 – AADT per Lane Density Map (30)

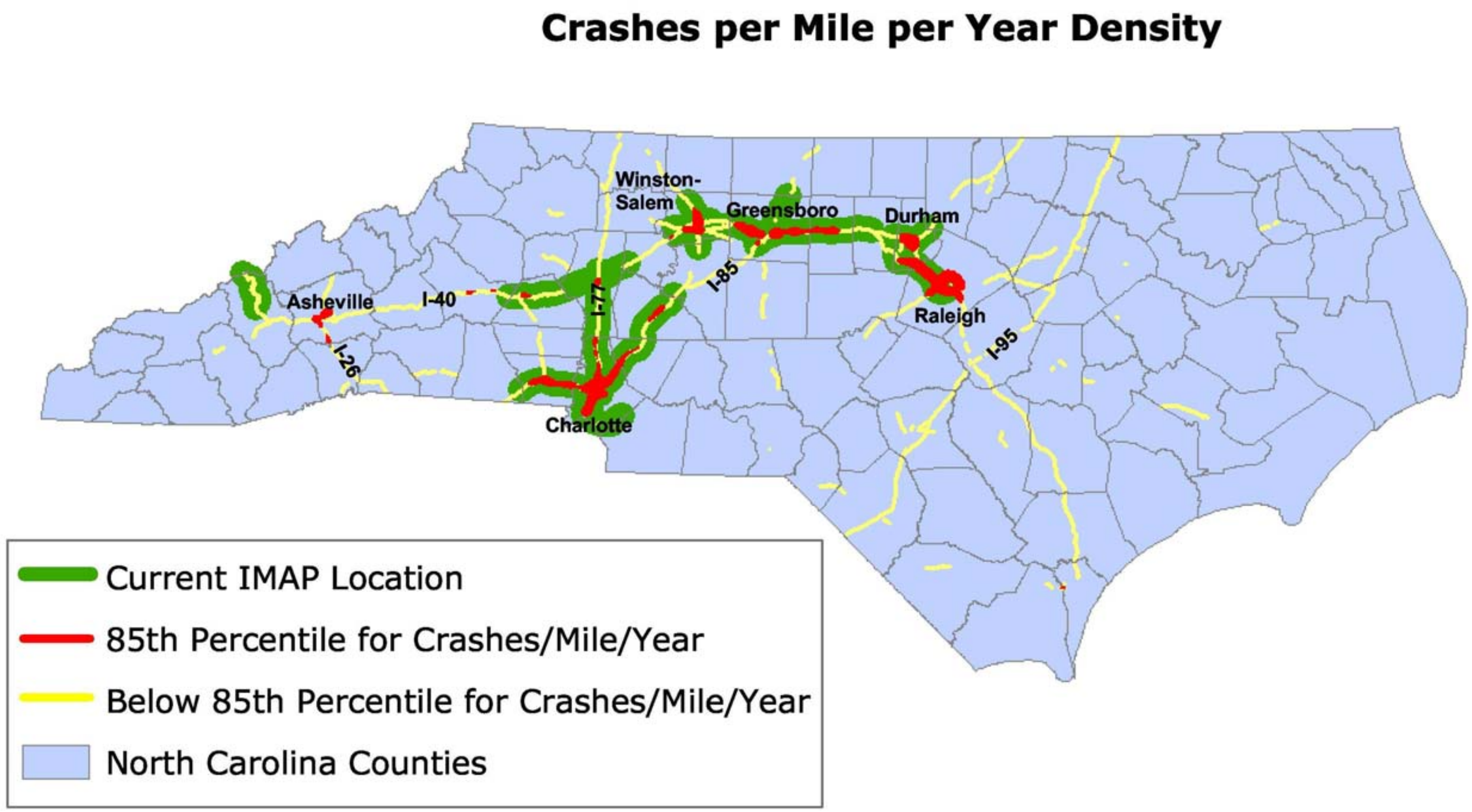


Figure 4.3 -- Crashes per Mile per Year Density Map (*32*)

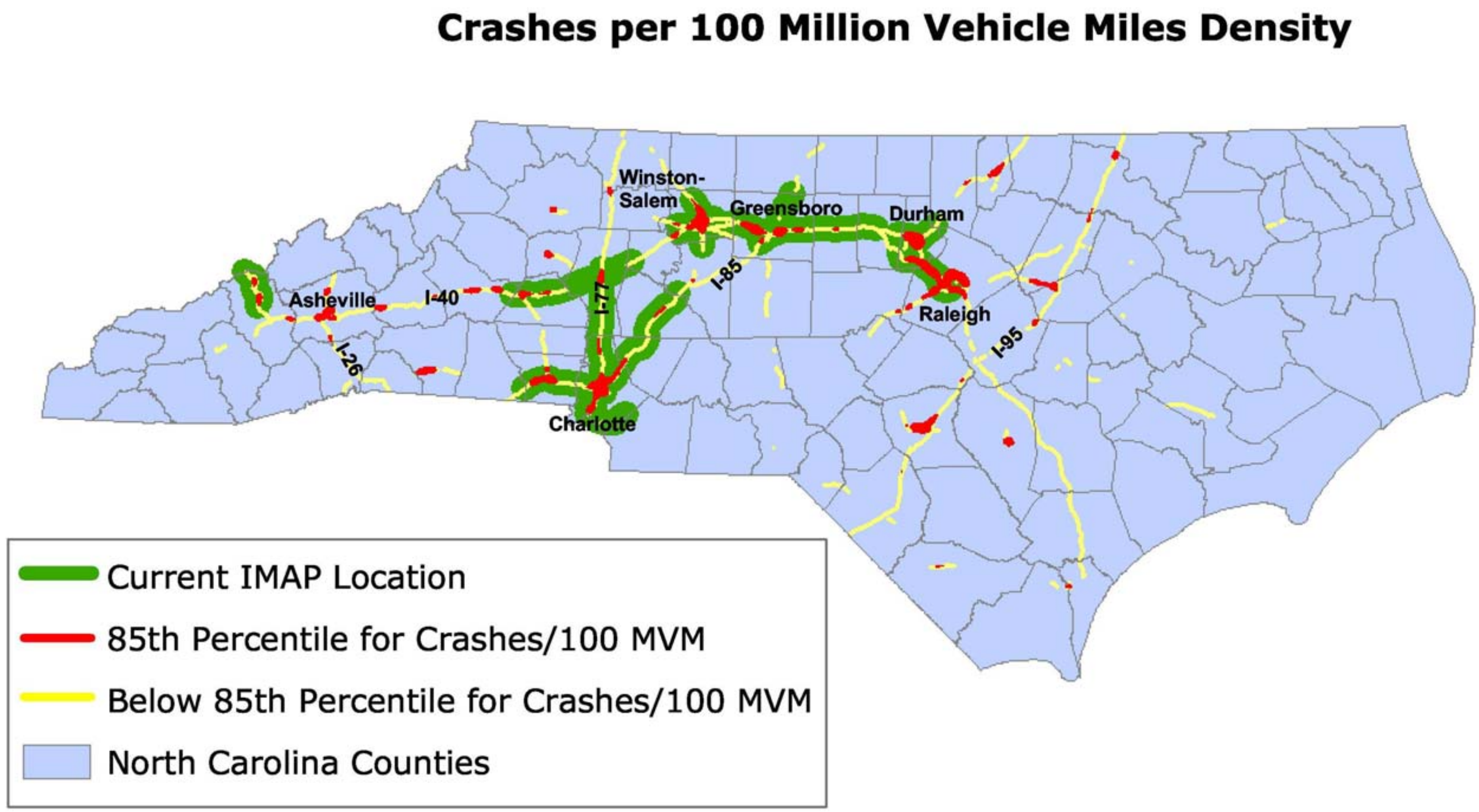


Figure 4.4 -- Crashes per 100 Million Vehicle Miles Density Map (30)

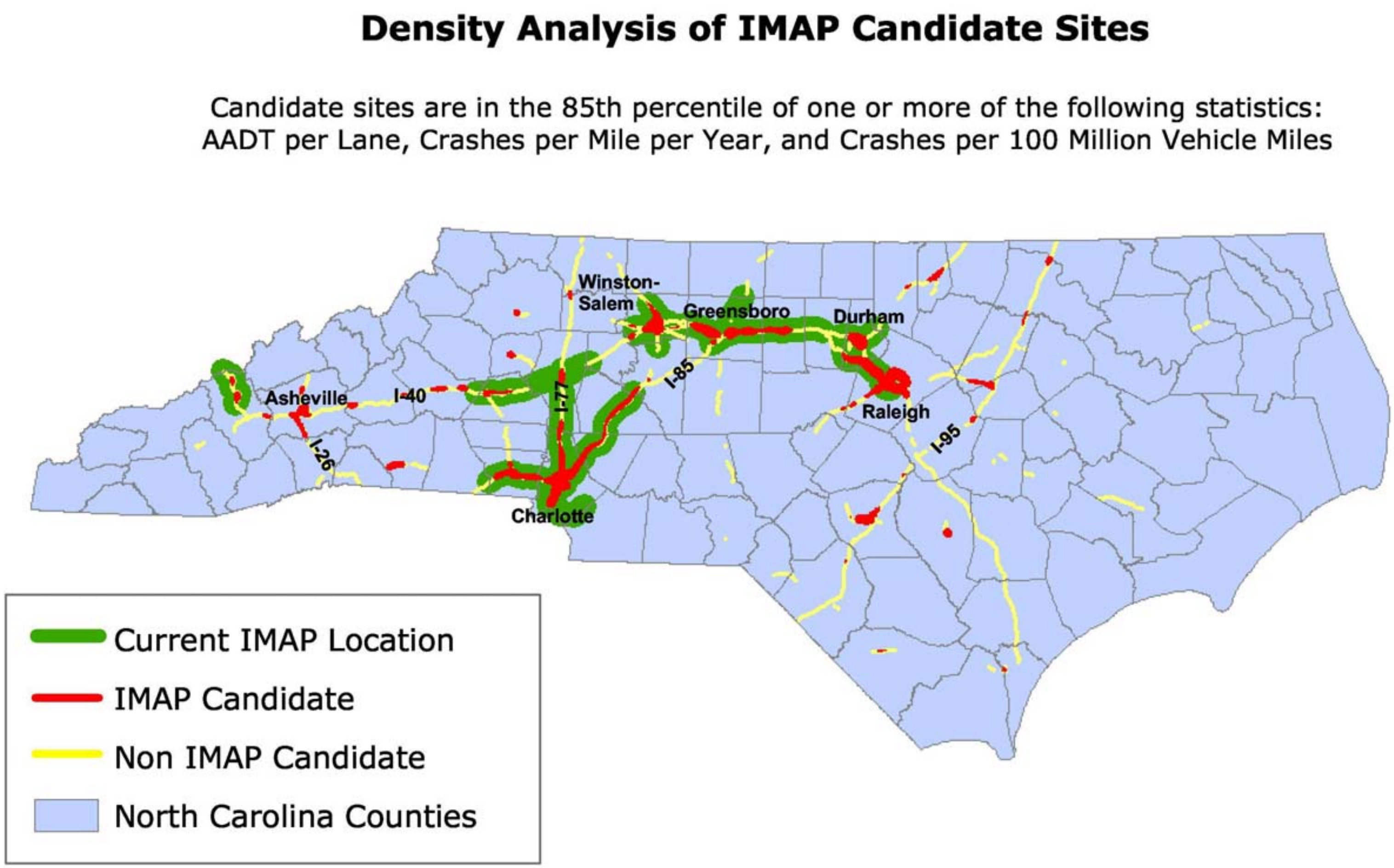


Figure 4.5 -- Density Map of IMAP Candidate Sites (31)

Planning Level Analysis

Planning analysis for the two candidate sites is consistent with the suggestion that the sites are quality expansion sites. The Raleigh site ranks in the 85th percentile or higher in all three categories in terms of crashes per 100 million vehicle miles and ranks highly according to the other criteria as well. In addition, the Asheville site was found to be in the 55th percentile or higher for all three categories of the same criteria. The complete planning level analysis, shown in Table 4.6, shows that both sites appear to be promising.

Table 4.6 – Planning Level Analysis Results for Candidate Sites

Category	**Criterion**	**Raleigh (percentile)**	**Asheville (percentile)**
Overall Statewide	Crashes per 100 MVM	85	65
Overall Statewide	Crashes per mile per year	90	70
Overall Statewide	AADT per lane	85	90
Non-IMAP Statewide	Crashes per 100 MVM	90	70
Non-IMAP Statewide	Crashes per mile per year	95	85
Non-IMAP Statewide	AADT per lane	95	95
IMAP Statewide	Crashes per 100 MVM	85	55
IMAP Statewide	Crashes per mile per year	85	50
IMAP Statewide	AADT per lane	70	85

Operational Level Analysis

Operational level assessment of the two candidate sites again established both sites as promising. Cost information for the two sites was assumed was based on the findings of Khattak and Rouphail (*32*). Values for IMAP vehicle operating costs per hour of $17.30 and $13.70 were assumed for the Raleigh and Asheville sites, respectively. The Raleigh figure was based on the average cost per vehicle for Division 5, while the Asheville figure was based on Division 12. It must be noted that Asheville is actually within Division 13, however no existing IMAP programs are found in Division 13 and so no cost information is available. Therefore, cost information of a nearby division was used and Division 12 was chosen over Division 14 due to the special case of the facility (Haywood County) in Division 14. Values of 15 hours per day and 250 days per year were estimated for each of the facilities to mimic common IMAP operation hours found in Table 4.1. As far as the number of vehicles for each site, the fleet size of five suggested by the model was accepted, and resulted in three roaming vehicles for both sites due to the assumed fleet size to roaming ratio (i.e. number of roaming vehicles is approximately one-half the fleet size). Finally, annual estimations for benefits and costs were determined and a summary of the information is shown in Table 4.7.

Table 4.7 – Operational Level Analysis Results for Candidate Sites

Category	**Raleigh**	**Asheville**
Number of Vehicles Roaming	3	3
Shoulder Incident Delay Savings (vehicle hours)	200	700
Single Lane Closure Delay Savings (vehicle hours)	20,100	70,500
Multiple Lane Closure Delay Savings (vehicle hours)	34,500	N/A
Total Delay Savings (vehicle hours)	54,800	71,200
Total Monetary Benefits	$822,000	$711,000
Total Costs	$194,600	$154,100
Annual B / C	4.22	4.62

The operational analysis concluded Raleigh and Asheville to both be promising locations for new IMAP programs. Both sites have annual benefits to costs ratios in excess of one. Overall it appears that each site should be considered for an IMAP program as planning and operational analyses suggested the sites would be promising candidates for IMAP service.

4.3 Sensitivity Analysis

An additional task completed for this thesis was the conduct of sensitivity analysis on several of the variables used in the operational analysis methodology for the Raleigh and Asheville sites. The variables that were examined included (a) the number of IMAP vehicles, (b) average distance between turnaround points, (c) response time without IMAP, (d) IMAP operating cost, (e) value of time, and (f) the annual number of IMAP operating hours. Each of the analyses is discussed separately below. For all sensitivity analyses, variables have default values equal to those used in the "default" application unless it is being used in the respective analysis. The default values are shown in Table 4.8.

Table 4.8 – Default Values for Variables

Variable	Raleigh	Asheville
Number of Vehicles Roaming	3	3
Turnaround Point Spacing	1 mile	2 miles
Response Time without IMAP	20 minutes	20 minutes
Cost of IMAP Vehicle per Hour	$17.30	$13.70
Value of Time per Hour	$15	$10
Annual Operating Hours	3750	3750

Number of Roaming IMAP Vehicles

The number of IMAP vehicles on a facility has a large impact on the benefits to costs ratio of IMAP programs because it is closely related to both benefits and costs. Table 4.9 displays sensitivity analysis summary information for the number of IMAP vehicles. As expected, costs increased by a constant rate (the annual cost of operating a single IMAP vehicle) with each additional vehicle. However, the total delay savings benefits increased at a much smaller rate with the addition of each additional vehicle on the facility. This led to the most impressive benefit to cost ratio occurring with only a single IMAP vehicle roaming on the facility (a factor of around three times more beneficial than the same site with four IMAP vehicles). Then again, the methodology presented in this project assumes that IMAP vehicles are always able to respond to incidents as soon as they become aware of them and that an IMAP vehicle is always available to respond to each incident. In actuality this is not true. Instead, on facilities where many incidents occur, an IMAP program may actually reach capacity, or the maximum number of incidents that can be responded to without abandoning or ignoring others.

To better model this, queuing theory could be used to estimate the percentage of time that an IMAP vehicle is available to respond to incidents. Specifically, an M/M/N model could reasonably model the facility where the arrival and service distributions are assumed to be random and the number of IMAP vehicles is determined on a site-specific basis (*33*). Using incident data, this method could estimate the number of vehicles that would be needed to service the expected number of incidents on the facility. Additionally, this modeling technique can estimate the percentage of incidents that will have increased response times (i.e., the responding IMAP vehicle must first help to clear a previous incident).

Another benefit of the M/M/N model suggested by May (*33*) is the ability to account for those occasions when incidents occur at a rate higher than the response rate of the IMAP program. In these cases, incidents are queued until IMAP vehicles are able to respond, resulting in longer response times. This increase in response time will increase the overall duration of the incident, resulting in additional delay. For this research, incidents were examined on an individual basis and assumed to occur independent of the influences of other incidents. In addition, an assumption was made that an IMAP vehicle was able to respond immediately to the incident. These assumptions will most likely lead to conservative estimations of delay. In general, the use of queuing theory could result in a better idea of how well particular numbers of IMAP vehicles are able to respond to expected incidents. However, the lack of incident data for this research prevented an attempt to accurately apply queuing theory. Agencies with incident data may wish to apply queuing theory to determine more accurate delay savings.

In taking this into consideration, decision makers looking to expand IMAP service must be aware that larger numbers of incidents will require more vehicles to respond. In addition, extra IMAP vehicles may add additional feelings of security to customers. More IMAP vehicles will increase the number of vehicles that are observed by drivers and will likely result in an increase in the overall customer satisfaction of the program.

Table 4.9 –Sensitivity of B/C Ratio to Number of Vehicles Roaming

Number of Trucks (Raleigh)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
1	47,200	$64,900	10.91
2	52,400	$129,800	6.06
3	54,800	$194,600	4.22
4	57,100	$259,500	3.30

Number of Trucks (Asheville)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
1	50,900	$51,400	9.90
2	65,700	$102,800	6.39
3	71,200	$154,100	4.62
4	74,500	$205,500	3.63

Turnaround Point Spacing

Turnaround point spacing represents the average distance between points on the facility where an IMAP vehicle can perform a u-turn. Theoretically, the shorter distance between turnaround points should lead to lower response times due to IMAP vehicles having to travel fewer miles when they need to turn around to respond to an incident. Table 4.10 shows the results from the sensitivity analysis. As expected, shorter distances between turnaround points does lead to lower response times and additional delay savings. However, it appears that a large change in average turnaround point spacing is required to significantly impact the benefits to costs ratio as the benefits to costs ratio decreased by less than 0.4 over the entire range. Still, it must be noted that the sensitivity analysis on turnaround spacing was done with three vehicles being present at each site. Perhaps with fewer vehicles at the site, larger impacts may be observed with varying distance between turnaround points. Additionally, the clearance times for all incidents are assumed the same with or without IMAP present. Therefore, the turnaround spacing impacts only the response time of the incident which commonly makes up less than one-third of the overall incident duration.

Table 4.10 – Turnaround Point Spacing Sensitivity Results

Spacing Between Turnaround Points (Raleigh)	**Total Delay Savings (Annual)**	**Total Costs (Annual)**	**Benefit / Cost**
0.5 miles	55,900	$194,600	4.31
1 mile	54,800	$194,600	4.22
1.5 miles	54,500	$194,600	4.20
2 miles	53,600	$194,600	4.13
2.5 miles	53,100	$194,600	4.09
3 miles	52,400	$194,600	4.04
3.5 miles	51,700	$194,600	3.99
4 miles	51,300	$194,600	3.95

Spacing Between Turnaround Points (Asheville)	**Total Delay Savings (Annual)**	**Total Costs (Annual)**	**Benefit / Cost**
0.5 miles	73,800	$154,100	4.79
1 mile	71,900	$154,100	4.67
1.5 miles	71,200	$154,100	4.62
2 miles	71,200	$154,100	4.62
2.5 miles	69,600	$154,100	4.52
3 miles	68,800	$154,100	4.46
3.5 miles	68,800	$154,100	4.46
4 miles	68,000	$154,100	4.41

Response Time without IMAP

The response time without IMAP directly impacts the incident durations of incidents where an IMAP program is not present. Longer response times lead to longer incident durations and increased delay. Additionally, this increase in incident duration is felt on all incidents that occur on the facility, regardless of other incident characteristics. The results of the sensitivity analysis for non-IMAP response time, Table 4.11, confirm these statements for the most part. Response times for non-IMAP vehicles appear to have a significant impact on delay savings benefits. However, the values presented in Table 4.11 do not appear consistent, especially for the values when the response time was in excess of 30 minutes. This can be attributed to the constraints of the delay estimation models. At 40 minutes the overall duration of more severe incidents exceeds the 60 minute limit of the delay models. Therefore, the delay is estimated with the 45-minute and 60-minute delay models. This leads to an underestimation of the actual delay expected. Still, the trends observed in the results, with knowledge of this minor shortcoming, suggests that the non-IMAP response time does greatly impact the benefits of implementing an IMAP program. Additionally, it can be seen that even with a very optimistic non-IMAP response time of 10 minutes the B/C ratio still exceeds one. This suggests that IMAP service can be beneficial regardless of non-IMAP response time for some facilities.

Table 4.11 – Non-IMAP Response Time Sensitivity Results

Non-IMAP Response Time (Raleigh)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
10 minutes	20,500	$194,600	1.58
20 minutes	54,800	$194,600	4.22
30 minutes	58,300	$194,600	4.49
40 minutes	53,800	$194,600	4.15
50 minutes	119,400	$194,600	9.20
60 minutes	93,800	$194,600	7.23

Non-IMAP Response Time (Asheville)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
10 minutes	22,700	$154,100	1.47
20 minutes	71,200	$154,100	4.62
30 minutes	143,300	$154,100	9.30
40 minutes	53,100	$154,100	3.45
50 minutes	121,200	$154,100	7.87
60 minutes	141,200	$154,100	9.16

Cost of IMAP Vehicle per Hour

Operating costs for IMAP vehicles are directly tied to the annual costs of an IMAP program. Therefore, as the cost of operating an IMAP vehicle increases, annual costs for the program will similarly increase. The results, shown in Table 4.12, support this relationship and show that vehicle operating costs can have significant impacts on the benefits to costs ratio for an IMAP program.

Table 4.12 – IMAP Vehicle Cost Sensitivity Results

Cost of IMAP Vehicle per Hour (Raleigh)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
$10	54,800	$112,500	7.31
$20	54,800	$225,000	3.65
$30	54,800	$337,500	2.44
$40	54,800	$450,000	1.83
$50	54,800	$562,500	1.46
$60	54,800	$675,000	1.22

Cost of IMAP Vehicle per Hour (Asheville)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
$10	71,200	$112,500	6.33
$20	71,200	$225,000	3.16
$30	71,200	$337,500	2.11
$40	71,200	$450,000	1.58
$50	71,200	$562,500	1.27
$60	71,200	$675,000	1.05

Value of Time

Similar to IMAP vehicle operating costs, the value of time variable directly impacts the benefits to cost ratio, from the benefits side of the equation. Because the equivalent monetary benefits are simply the delay savings multiplied by the value of time, the equivalent monetary benefits vary proportionally to changes in the value of time. Table 4.13 displays the results of the sensitivity analysis, which confirms this trend.

Table 4.13 – Value of Time Sensitivity Results

Value of Time (Raleigh)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
$10	54,800	$194,600	2.82
$15	54,800	$194,600	4.22
$20	54,800	$194,600	5.63
$25	54,800	$194,600	7.04
$30	54,800	$194,600	8.45

Value of Time (Asheville)	Total Delay Savings (Annual)	Total Costs (Annual)	Benefit / Cost
$10	71,200	$154,100	4.62
$15	71,200	$154,100	6.93
$20	71,200	$154,100	9.24
$25	71,200	$154,100	11.55
$30	71,200	$154,100	13.86

Annual Hours of Operation

Much like the hourly cost of an IMAP vehicle, the annual numbers of hours of operation for the IMAP program directly impact the annual costs of the program as well as the B/C ratio. From the results of the sensitivity analysis, shown in Table 4.14, it can be inferred that the annual number of hours that an IMAP program operates has a profound effect on the annual cost of the program. However, these results may be a little misleading on the benefits side of the ratio. An implicit assumption in the methodology is that IMAP vehicles on the facility are able to respond to all of the estimated incidents. However, with a low number of operating hours, this would not be true. For example, 1000 hours annually breaks down into only four hours per work day approximately. It is tough to imagine that an IMAP program operating only four hours per work day could respond to incidents in both the peak and off-peak time periods (as peak hours are estimated to be 7-9 am and 4-6 pm). Therefore, it is important to take into consideration this assumption when determining the hours of operation for an IMAP program.

Table 4.14 – Annual Operating Hours Sensitivity Results

Annual Hours of Operation (Raleigh)	Total Delay Savings (Annual)	Total Roaming Costs (Annual)	Benefit / Cost
1000	54,800	$51,900	15.84
2000	54,800	$103,800	7.92
3000	54,800	$155,700	5.28
4000	54,800	$207,600	3.96
5000	54,800	$259,500	3.17
6000	54,800	$311,400	2.64
7000	54,800	$363,300	2.26
8000	54,800	$414,800	1.98

Annual Hours of Operation (Asheville)	Total Delay Savings (Annual)	Total Roaming Costs (Annual)	Benefit / Cost
1000	71,200	$41,100	17.32
2000	71,200	$82,200	8.66
3000	71,200	$123,300	5.77
4000	71,200	$164,400	4.33
5000	71,200	$205,500	3.46
6000	71,200	$246,600	2.89
7000	71,200	$287,700	2.47
8000	71,200	$328,500	2.17

Sensitivity Analysis Summary

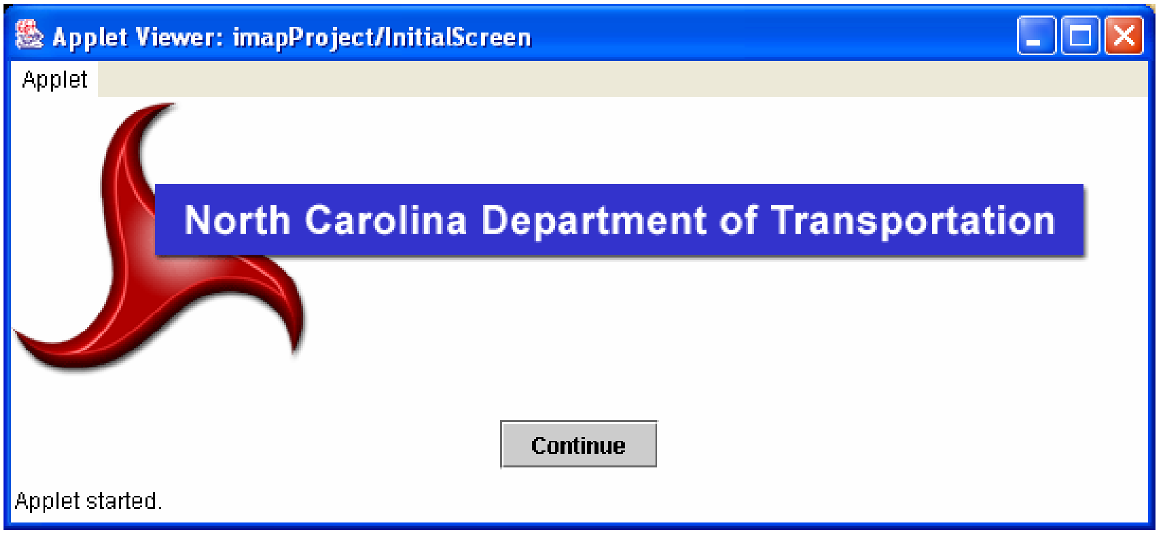
Given the results of the sensitivity analysis of the B/C ratio for the various IMAP variables, several conclusions can be drawn. Overall, the cost of operation of an IMAP vehicle and the value of time appear to be the most consistent, significant influences on the B/C ratio. Non-IMAP vehicle response time also appears to have a significant influence on the B/C ratio, but there are some inconsistencies in the results. This is most likely due to the lack of delay models for estimating incident durations over 60 minutes (resulting in a conservative estimate of delay for these incidents). Additionally, the number of IMAP vehicles roaming and the annual hours of operation appear to have significant impacts on the B/C ratio, but with issues (discussed above) that must be addressed by decision-makers. Finally, turnaround spacing has little impact on the benefits to costs ratio due to the minor impacts it has on response times.

4.4 Decision-Support Tool

A key product of this thesis is a decision-support tool that implements the methodology that was developed in a user-friendly way. This tool allows easy comparison of potential IMAP expansion sites in terms of rankings and benefits to costs ratios. The tool allows users to analyze existing or future IMAP facilities using planning level analysis and operational analysis. In addition, if desired, it can perform analysis of single incidents occurring on a facility. Together, they encompass making decisions about IMAP implementation.

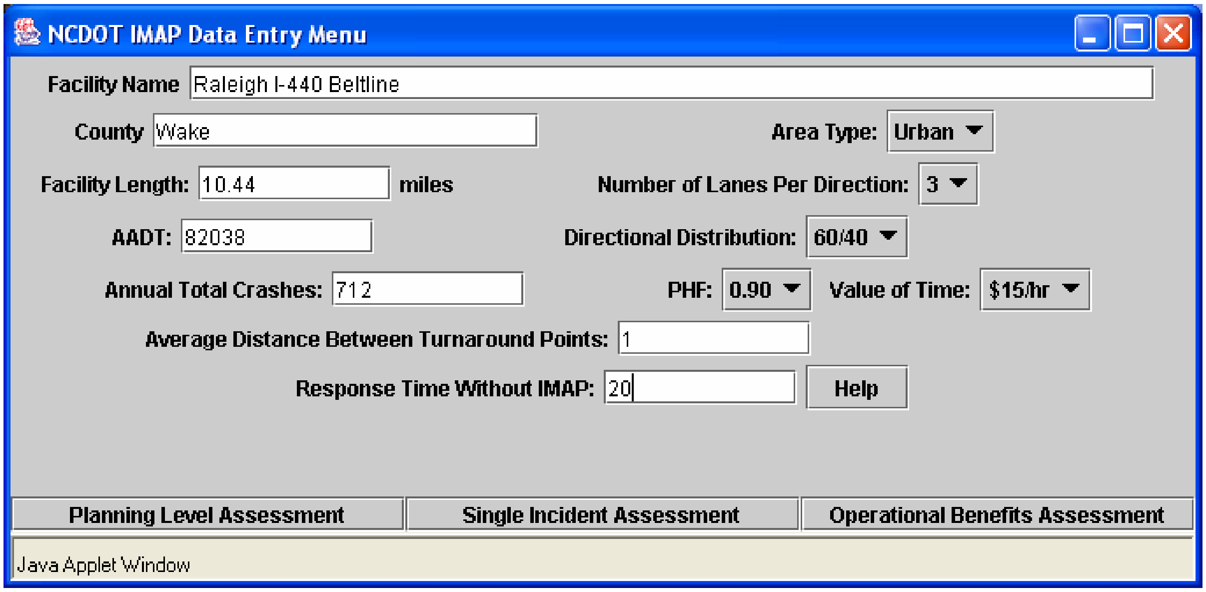
The decision support tool was developed using the Java computer language. Java is an object-oriented language that can easily be run on most computers today. Code for the decision support tool was written using version 1.4.1 of the Java 2 Standard Development Kit (J2SE SDK). The following section describes each screen in the tool, including a display of each screen.

Introduction Screen



Continue – Continue button must be pushed to begin. Pressing the continue button will proceed to the Facility Data Entry Screen.

Facility Data Entry Screen



<u>Facility Name</u> – Enter the name of the facility that is being considered for IMAP installation. This field is open and allows the user to enter in any text (up to 50 characters). This field must be filled (entry required) in order to continue to other sections of the tool.

<u>County</u> – Enter the name of the county where the facility is located. This field is open and allows the user to enter in any text (up to 20 characters). This field is not required (optional) in order to continue to other sections of the tool.

<u>Area Type</u> – Select the general area type of the facility. Urban areas are typically characterized by a free flow speed of 70 mph, short interchange spacing (average of one mile) and low truck percentages (~5%). Rural areas typically have higher free flow speeds of

75 mph, longer interchange spacing (2+ miles) and relatively higher truck percentage (~10%) trucks. This entry is required.

Facility Length – Enter the length of the facility that is considered for IMAP patrol, in center-line miles. This field is restricted to numbers with up to 15 decimal numbers allowed. This entry is required.

Number of Lanes per Direction – Select the average number of travel lanes per direction for the facility. This number can vary from 2 to 5 lanes only. This entry is required.

AADT – Enter the most recent (or as appropriate the projected) Average Annual Daily Traffic (AADT) for the facility. This field is restricted to integer values. This entry is required.

Directional Distribution – Select the closest directional distribution of traffic volumes on the facility to the indicated values. This entry is required.

Annual Total Crashes – Using most recent data, enter the average number of total crashes that occurred on the facility in a year (or average of the last 2-3 years). This field is required.

Peak Hour Factor (PHF) – Select appropriate peak hour factor PHF for the facility. This entry is required.

Value of Time – Select the average value of time per hour for the users of the facility. This value will enter into the benefit calculations for the facility. This field is required.

Average Distance Between Turnaround Points – Enter the average distance between points within the facility at which an IMAP vehicle is able to change directions. These points may include interchanges and median breaks that allow U-turns. This field is required.

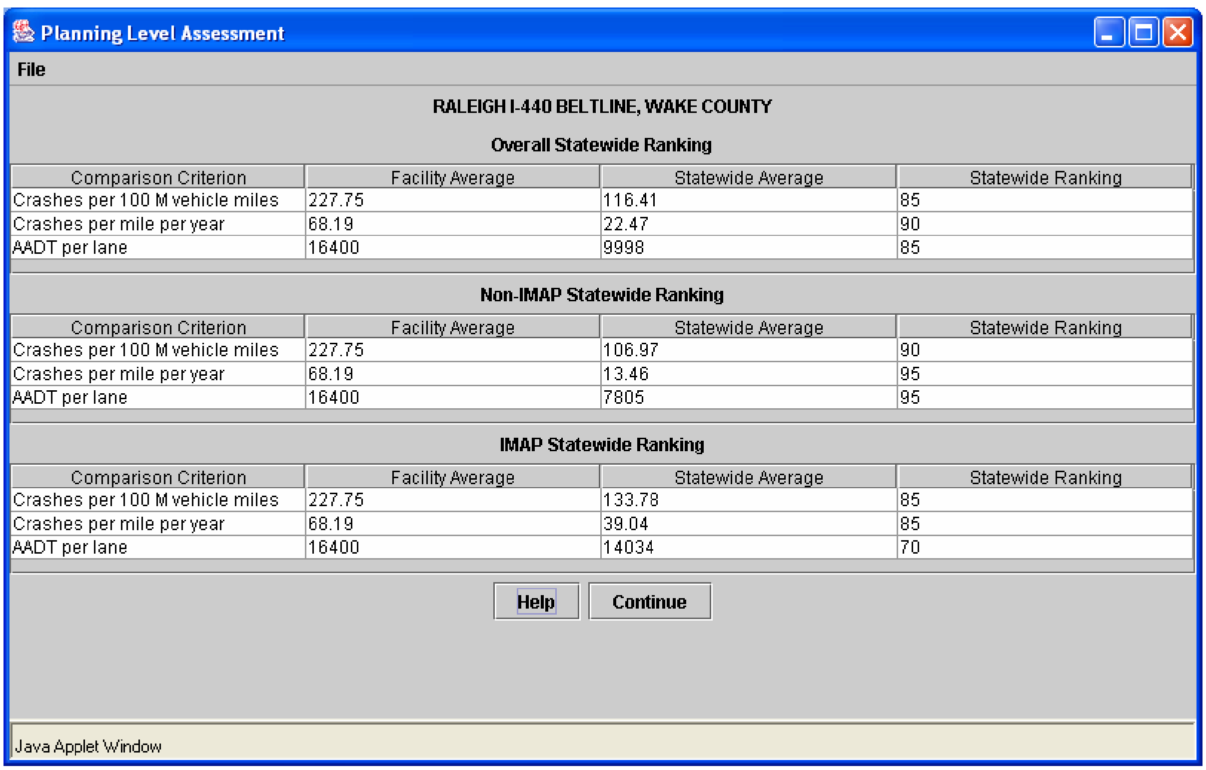
Response Time Without IMAP – Enter the response time that is required for responding vehicles without IMAP. These vehicles may include police vehicles or tow trucks. This field is required.

Planning Level Assessment – When pressed, the tool will execute a Planning level analysis of the candidate site. This analysis will provide the ranking of the candidate facility with respect to statewide, IMAP only, and non-IMAP only sites in the state of North Carolina. This entry is optional.

Single Incident Assessment – Allows the user to produce detailed estimates of the benefits of an IMAP for a single incident with user-defined incident characteristics. This entry is optional.

Operational Benefits Assessment – When pressed, the tool will execute an Operational level analysis of the candidate site. This analysis will provide estimates of annual implementation costs, added user benefits and the cost benefit ratios should an IMAP program be implemented for the facility. This entry is optional.

Planning Level Assessment Screen



Overall Statewide Ranking

Comparison Criterion	Facility Average	Statewide Average	Statewide Ranking
Crashes per 100 M vehicle miles	227.75	116.41	85
Crashes per mile per year	68.19	22.47	90
AADT per lane	16400	9998	85

Non-IMAP Statewide Ranking

Comparison Criterion	Facility Average	Statewide Average	Statewide Ranking
Crashes per 100 M vehicle miles	227.75	106.97	90
Crashes per mile per year	68.19	13.46	95
AADT per lane	16400	7805	95

IMAP Statewide Ranking

Comparison Criterion	Facility Average	Statewide Average	Statewide Ranking
Crashes per 100 M vehicle miles	227.75	133.78	85
Crashes per mile per year	68.19	39.04	85
AADT per lane	16400	14034	70

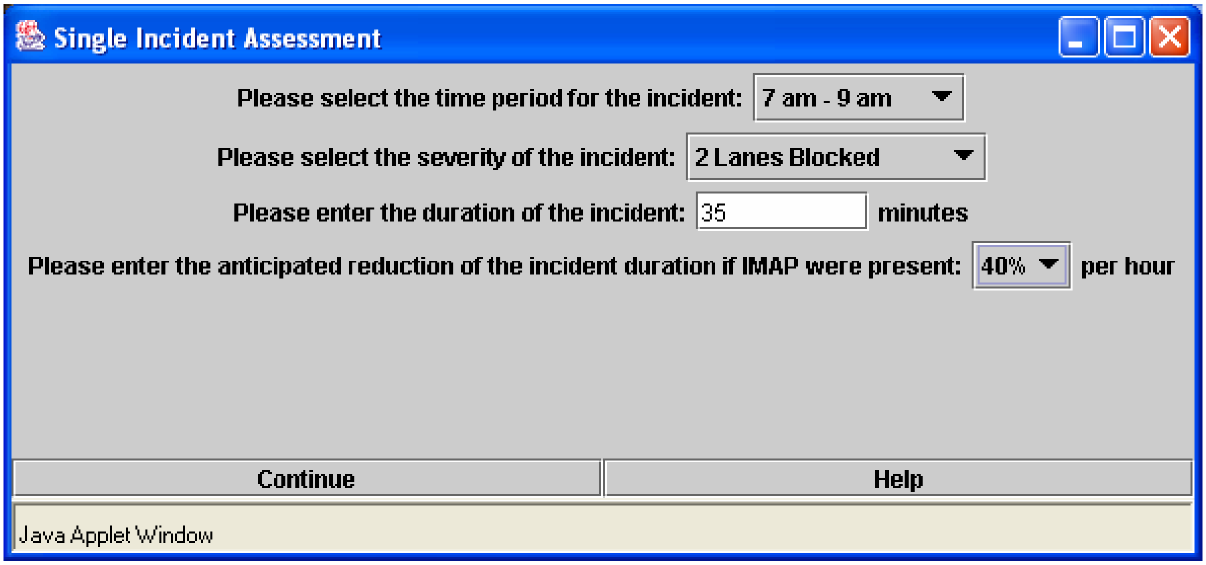
The three criteria for comparison shown on the leftmost column are described in the methodology section of the report. The information below is provided solely for the interpretation of the tool results. Three comparisons are made: facility against statewide data (top box); facility against non-IMAP sites only (middle box); and facility against IMAP-only sites (lower box).

Facility Average – These are the average values for each of the 3 comparison criterion for the facility as computed from the entries to the Data Entry Screen. These values are the same for all boxes.

Statewide Average – These are the average values for each of the 3 comparison criterion for the facility as computed from the entries to the Data Entry Screen. These value vary depending on whether all (top box), non-IMAP (middle) or IMAP-only (bottom) sites are compared with the candidate site.

Statewide Ranking – Percentile rankings for the respective 3 comparison criteria for each of the ranking categories (Overall Statewide, Non-IMAP Statewide, and IMAP Statewide rankings). This value represents the percentage of statewide (or IMAP-only, etc.) facilities that have a comparison criterion value that is less than the facility average for the given ranking category. For example, a 90th percentile ranking for crashes per 100MVM in the middle box indicates that the candidate site is in the top 10 percent of all non-IMAP sites for that criterion.

Single Incident Assessment Screen



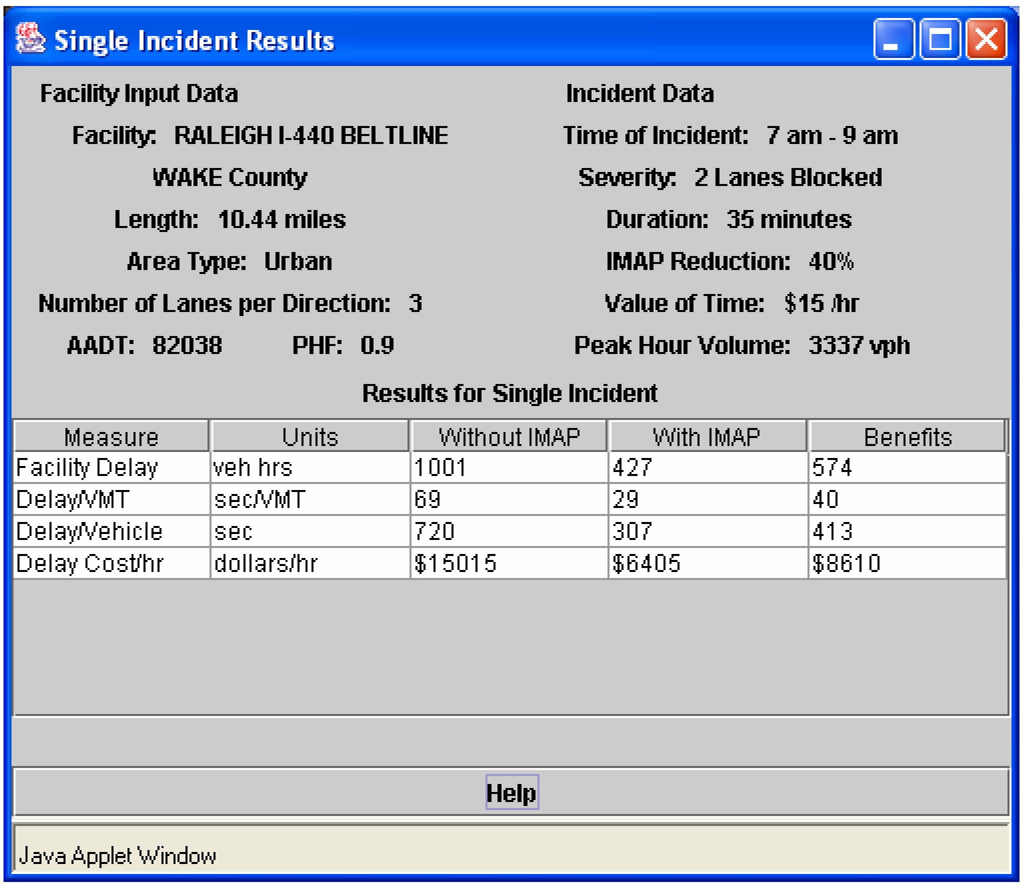
Time Period – Select the time period from the list in which the single incident being examined occurs. The time period is used to pick the appropriate hourly volume factor from the urban or rural volume profiles. This entry is required

Severity – Select the severity of the incident (shoulder closure, single lane blockage, etc.) from the pull down menu. This entry is required.

Duration – Enter the duration of the incident assuming that no IMAP program has been implemented on the facility. This represents the total time starting from the occurrence (or first notification) of the incident until the incident is completely cleared and the normal roadway capacity resumes. This field is required.

Reduction of Incident Duration with IMAP – From the pull-down menu, select the percentage of reduction of the total incident duration that would be expected if an IMAP program were to be implemented on the facility. This field is required.

Single Incident Results Screen



The benefits of a single incident are summarized in this screen. The top portion of the screen gives the input echo data items which describe the facility and incident characteristics. The following items describe the tabulated output.

Measure – Describes the delay value type that is used for comparison of results. This includes facility delay, delay per VMT, delay per vehicle, and delay cost per hour (based on the value of time as entered by the user).

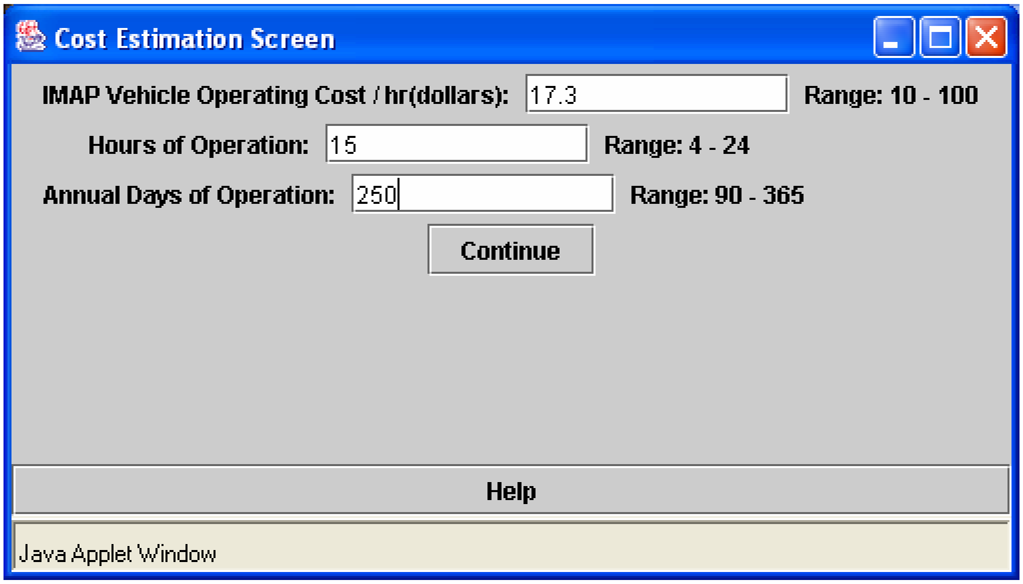
Units – Displays the units of the respective measure.

Without IMAP – Estimated delays (in the displayed units) that are incurred due to the facility and incident characteristics (shown on the upper half of the screen). This column assumed that no IMAP program has been implemented for the facility.

With IMAP – Estimated delays (in the displayed units) that are incurred due to the facility and incident characteristics (shown on the upper half of the screen). This column assumed that an IMAP program has been implemented for the facility.

Benefits – Displays the difference between the Without IMAP and With IMAP categories.

Cost Estimation Screen



IMAP Vehicle Operating Cost – Enter the estimated cost of operating a single IMAP vehicle for one hour on the proposed facility. This value must be in the range of 10 to 100 dollars and the entry is required.

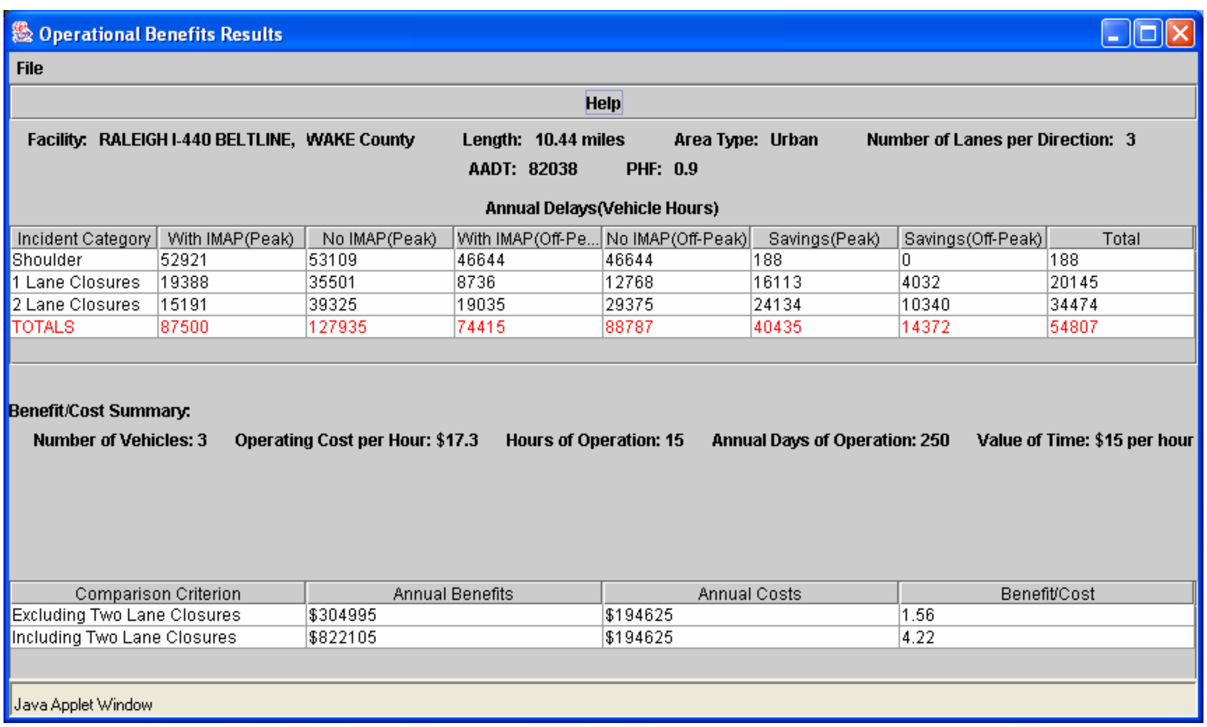
Hours of Operation– Enter the number of hours the IMAP program operates on an average day. This value must be in the range of 4 to 24 hours and is required to continue.

Annual Days of Operation – Enter the number of days the IMAP program operates per year. This value must be in the range of 90 to 365 days. This entry is required.

Fleet Size Estimation Screen

This screen allows the user to accept an estimated number of required IMAP vehicles in the fleet, based on current statewide IMAP sites. Optionally, the user can override this estimate with a preferred number of vehicles. This entry is required.

Operational Level Assessment Screen



The overall benefits and costs are summarized in this screen. The top and middle portions of that screen give the input echo data items which describe the facility and IMAP fleet characteristics. The following items describe the tabulated output.

Incident Category – Describes the category of incidents based on severity. It includes shoulder closure, 1 lane closure and 2+ lane closures (only for facilities with 3+ lanes per direction).

With IMAP - Estimated total annual delays in veh.hrs that are incurred due to the indicated incident category and for the indicated time period (peak or off peak—see definition below). This column assumed that an IMAP program has been implemented for the facility.

No IMAP - Estimated total annual delays in veh.hrs that are incurred due to the indicated incident category and for the indicated time period (peak or off peak—see definition below). This column assumed that no IMAP program has been implemented for the facility.

Peak – Refers to delays that are estimated to occur during peak hours only. This category represents delays that occur during all peak hours in a day.

Off-Peak – Refers to delays that are estimated to occur during off-peak hours only. This category represents delays that occur during all off-peak hours in a day.

Savings – Displays the difference in estimated annual delays (in veh.hrs) between the No IMAP and With IMAP categories. These values are reported in separate columns for the peak and off-peak hours, respectively.

Total – Displays the total delays savings expected for the facility for the given Incident Category. This value is the sum of peak and off-peak hour savings.

Annual Benefits – Displays the total annual savings in dollars resulting from the annual delays savings computed earlier. This value is computed assuming two levels of incident severities namely (a) those that exclude two lane closures, and (b) all incidents. The user should remember that no full roadway closures can be modeled with this tool.

Annual Costs – Displays the estimated total annual costs in dollars for operating an IMAP program at the indicated fleet size on the facility. These values are based on fleet data entered by the user in the cost estimation screen.

Benefit/Cost – Displays the estimated Benefit to Cost (B/C) ratio of the IMAP program for the candidate facility. This ratio represents the total annual benefits divided by the annual costs for the proposed IMAP program.

CHAPTER 5 – SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This research develops a novel methodology for determining the benefits of existing IMAP programs in North Carolina as well as identifying promising IMAP deployment sites. The methodology includes the estimation of incident-induced delays as well as the benefits and costs associated with an IMAP program. These analyses allow for the comparison of expansion sites to determine the most beneficial facilities for IMAP expansion.

The planning level analysis allows agencies that may not have incident data readily available to consider the merits of introducing IMAP service through a comparison of traffic demands on the facility to those of freeway facilities statewide. Even when crash data are available for the facility, the planning level analysis still provides a beneficial screening process that can be used to identify promising candidate sites based on congestion and safety levels.

Besides the pioneering planning level analysis, the operational level analysis developed by this thesis presents novel approaches to the subject. Annual incidents were categorized in terms of impact (shoulder, single lane, etc) and time of day (peak and off-peak) for analysis as opposed to more generalized, average incidents reported in previous studies. The breakdown of incidents into response time and clearance time also presented an opportunity to vary response times based on the facility attributes (length and turnaround spacings) and the size of the IMAP fleet. Varying response times in this manner is a unique feature that no one has previously incorporated. This provides a better method for relating expected response times to the facility because it takes into account the ability of IMAP vehicles to roam on the facility and make u-turns, as would occur on the facility if an IMAP were installed. In addition, the use of FREEVAL to estimate delay based on HCM concepts, which consider the fact that some of the delayed vehicles may not have discharged from the system after the simulation time, presents better accuracy in delay estimation. This thesis is among the first to utilize these concepts in examining IMAP services and is superior to previous attempts, which made use of simple deterministic queuing. Furthermore, the idea of estimating the vehicle fleet size and number of roaming vehicles is usually not included as a part of an IMAP program. While many previous studies of IMAP programs examined the number of vehicles used at existing facilities, no attempts were made to estimate the number of vehicles needed for expansion sites.

Finally, a beneficial product of this project is the decision-support tool that integrates the methodology that was developed into an easy-to- use software tool. This tool provides decision makers with a method for comparing potential expansion sites on multiple analysis levels through a comparison of freeway facility rankings and potential benefits/costs resulting from IMAP program expansion.

5.2 Conclusions

Key findings of this thesis include:

1) Current methods for comparing potential IMAP expansion sites are very limited. To date, only a single study has been directed at this issue, leaving a large deficiency in the existing literature that are available when agencies are making the decision of where to expand new IMAP services. Even studies that examine the benefits and costs of existing IMAP services lack the ability to be readily applied to other programs without significant data and labor needs.

2) The planning level analysis presented in this thesis provides an initial comparison and ranking of freeway sites. This analysis can be used to identify an initial pool of potential sites that may be examined further for IMAP expansion.

3) In general, existing IMAP sites in North Carolina appear to be very cost-effective (i.e. B/C ratios greater than one). With a statewide B/C ratio over five, it appears that IMAPs in the state have been placed on facilities that have benefited from their presence. However, not all IMAP sites in the state appear to be cost-effective. Sites with fewer crashes, especially crashes per lane, appear to have fewer benefits.

4) The potential IMAP expansion sites, identified through planning level and GIS analysis, appear to be promising sites for IMAP expansion with expected B/C

ratios in excess of four. As a result of this conclusion, NCDOT recently began IMAP service on the I-440 facility in Raleigh.

5) Sensitivity analysis of IMAP program variables indicated that IMAP vehicle costs and non-IMAP response times were among the most influential on the B/C ratio of the program. Conversely, turnaround point spacing appeared to have very little impact on the annual benefits for the facility.

6) The decision support tool created during this thesis provides easy access to the methodology developed for use by decision makers. This software allows users to complete planning and operational level analyses for potential sites. In addition, this tool supplies a means for examining the benefits for a single incident on the facility.

5.3 Recommendations

This section provides a short list of suggestions for the improvement of the IMAP program within NCDOT. The suggestions, mostly dealing with improved data collection or data management, were identified in the course of conducting this research.

- Expanded efforts to collect data related to incident frequency and incident duration are needed to better estimate total annual incident characteristics (i.e. incident distribution tree) for freeway facilities. Limited data were available for this thesis and additional data would produce better estimations of annual delay benefits due to a better estimate of annual incident to crash ratio.

- While the methods developed by this project were intended for the analysis of North Carolina IMAP sites, other states should find the results beneficial as they face similar circumstances in trying to determine promising sites in expanding IMAP services. Specifically, agencies dealing with IMAP programs in areas ranging from rural to medium sized urban areas (similar to those examined in this thesis) may find the results most applicable. The application of the methodology developed within this research to other states would require the collection of state-specific percentile breakdowns for the planning level analysis as well as state-specific data related to incident characteristics (including a non-crash to crash ratio, incident durations, and incident severities), traffic volumes, and existing IMAP fleet sizes. Once this data becomes available, hard-coded values could be altered within the program code to reflect this data.

- Delay models used in this project were developed including incidents with durations up to 60 minutes. Future research should consider incidents with larger overall durations so that the delay for all incidents could be estimated directly (i.e. without the extrapolation used in this thesis).

- A suggested relationship between IMAP fleet size and number of roaming IMAP vehicles on a facility is suggested to be one-half of the fleet roaming during IMAP hours of operation. In actuality, this may not be true everywhere, and research is needed to study this relationship further. Specifically, facility-optimal vehicle fleet sizing based on incident data and site features could be examined.

- A more thorough analysis on the effects of IMAP placement should be conducted for IMAP operating hours, patrol route lengths, number of patrol vehicles, time periods in which incidents occur, and variations in roadway geometries (especially related to shoulder width and availability). Further examination of these areas can lead to a more responsive and comprehensive decision-support tool.

- Additional impacts such as fuel savings, emissions reductions, and reductions in secondary incidents should be added to better reflect the full benefits of IMAP programs. Additional costs, such as IMAP driver injuries or fatalities, could also be included in future study.

- An examination of the implementation of an IMAP on a temporary basis would also be beneficial. These occasions may include holidays or special events among others. While the potential benefits are significant, the methodology developed for this project does not adequately address the issue.

- This project focused on IMAP programs as a beneficial and promising incident management strategy that operates independently. However, IMAP programs may be most beneficial as part of an integrated ITS architecture. In this setting, IMAP programs are able to benefit from additional resources such as surveillance systems, telecommunication links, transportation management centers, traveler information systems, and additional interagency resources. Additional incident mitigation measures could be added or the decision-support tool could be expanded to include other ITS strategies.

- Data standardized across the state would prove beneficial to NCDOT as well as future research. Individual NCDOT divisions would collect the same information from their driver logs, leading to more universal data throughout the state. In addition, an increased effort to collect incident response and clearance times would prove advantageous. NCDOT, as well as researchers, would have a better grasp on incident durations and the breakdown of these incidents into response and clearance times. Times could be collected with the simple use of a stopwatch.

- IMAP driver logs should be entered into a uniform database format upon receipt. IMAP driver logs provide valuable information and should be analyzed. By entering the information into a database, the information becomes available and manageable for future needs. Also, the same database should be utilized by all NCDOT divisions to ensure similar data structure for all divisions.

- A suggestion for efficient data collection is to provide portable data management devices to IMAP drivers. These devices can range from PDA's to small personal computers. With technology of this manner, IMAP drivers could enter data directly into digital format without the need to fill out paper forms. This would eliminate a number of errors as well as eliminating the time needed to transfer the data from paper form to a database.

- IMAP service boundaries should not follow patrol boundaries, as they currently do, unless absolutely necessary. While the division boundaries may be easiest to administer, traffic congestion and incidents do not adhere to the same boundaries. Therefore, IMAP routes should be established according to where they are needed and not only where they are needed within a single division.

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APPENDIX A – PLANNING LEVEL ANALYSIS

Planning level analysis of a potential or existing IMAP facility allows for a broad comparison of the site, relative to the rest of the state of North Carolina using three separate measures of effectiveness (MOEs) pertaining to traffic and crash levels. Specifically, these measures are crashes per 100 million vehicle miles (100 MVM), crashes per mile per year, and average annual daily traffic (AADT) per lane. It should be noted that crashes are used due to the availability of crash data, but crashes are a surrogate for the broader category of incidents (including crash and non-crash incidents). Three measures are used due to the possibility of crash, incident, or AADT data being unavailable for a candidate site. As long as one of these values is available for the facility, an analysis with at least one of the measures can be done. In addition, the use of three measures gives a broader base for the ranking of the facility by taking into account measures using AADT and crash values for the facility. The three MOEs are calculated according to equations A.1 – A.3 at both the statewide and facility levels. Once this is done, the facility level measures can then be ranked according to the statewide percentile values, as follows:

$$CMVM = \frac{100000000 * AANC}{AADT * Length * 365} \qquad \text{(Equation A.1)}$$

$$CMY = \frac{AANC}{Length} \qquad \text{(Equation A.2)}$$

$$AADT\ per\ lane = \frac{\left[AADT * \left(\frac{DD}{100}\right)\right]}{NLD} \qquad \text{(Equation A.3)}$$

Where:

CMVM = Crashes per 100 million vehicle miles
AANC = Annual average number of crashes

CMY = Crashes per mile per year
DD = Directional distribution
NLD = Number of lanes per direction

The Statewide MOEs component of the Planning Level calculated values for the MOEs for every freeway segment within the State of North Carolina. This was accomplished using data from the Statewide Historical Data component of the Data section. Once these values were determined for all of the sites, the results were compiled for each MOE separately and percentile breaks were established. These percentiles represented the measures for overall statewide rankings as all sites were included. A more detailed breakdown was then accomplished through two additional applications of the same process using only those sites that currently are without an IMAP program and only those sites that currently do have an IMAP program. This resulted in the three categories of ranking scales of overall statewide rankings, statewide non-IMAP rankings, and statewide IMAP rankings.

Once the percentile scales for statewide MOE values were established, the MOE values were calculated for the individual facility in the Facility MOEs component of the Planning Level. Finally, the facility MOE values are ranked according to the statewide percentile scales for each of the three measures and each category (overall statewide rankings, statewide non-IMAP rankings, and statewide IMAP rankings) in the Rankings and GIS section of the Planning Level. The results are the percentile rankings for the various measures and categories for the facility that suggest that, for the given measure/category combination, a facility that has a higher percentile value than the corresponding statewide percentile is ranked as superior to the statewide group. For example, a facility ranking in the 65th

percentile of AADT per lane in the statewide non-IMAP category has a higher AADT per lane value than 65 percent of non-IMAP freeway facilities statewide. In addition, the measures for various facilities can be displayed in a GIS environment, according to statewide value percentiles, to see spatially the relationship of the facility to other sites in North Carolina. This is done by displaying sites that rank at the 85th percentile or higher in at least one of the three measures. This makes it relatively easy to identify high-impact locations (i.e. those facilities ranking at the 85th percentile, or higher, level for one of the three measures).

APPENDIX B – DELAY MODELS

Table B.1 – Rural Delay Models

Rural							
Model Number	**Lanes**	**Duration (min)**	**Severity**	**Equation**	**Trend Line R^2**	**P-Value of Variable**	**Standard Error**
1	2	15	Shoulder	$0.2241 e^{3.3497x}$	0.8973	0.0535	2.2554
2	2	15	1 Lane Blocked	$0.8273 e^{1.4213x}$	0.9964	0.0082	3.2703
3	2	30	Shoulder	$0.1338 e^{4.0456x}$	0.8380	0.0938	4.5263
4	2	30	1 Lane Blocked	$7.6142 x^{2.39}$	0.9973	0.0018	4.1605
5	2	45	Shoulder	$0.0874 e^{4.6202x}$	0.7968	0.1192	7.3195
6	2	45	1 Lane Blocked	$14.421 x^{2.5209}$	0.9984	0.0014	8.2550
7	2	60	Shoulder	$0.0615 e^{5.0878x}$	0.7706	0.1342	10.3425
8	2	60	1 Lane Blocked	$23.904 x^{2.7703}$	0.9952	0.0002	8.2601
9	3	15	Shoulder	$0.0977 e^{4.0555x}$	0.9203	0.0498	1.9444
10	3	15	1 Lane Blocked	$0.1484 e^{2.7794x}$	0.9959	0.0189	3.8158
11	3	15	2 Lanes Blocked	$2.5949 e^{0.5141x}$	0.9993	0.0016	1.9518
12	3	30	Shoulder	$0.0656 e^{4.6082x}$	0.8830	0.0805	3.3299
13	3	30	1 Lane Blocked	$4.324 x^{4.2185}$	0.9896	0.0015	3.3342
14	3	30	2 Lanes Blocked	$13.167 e^{0.3841x}$	0.9788	0.0078	7.6314
15	3	45	Shoulder	$0.041 e^{5.2607x}$	0.8409	0.1108	5.7174
16	3	45	1 Lane Blocked	$6.9167 x^{4.5917}$	0.9682	0.0008	5.0520
17	3	45	2 Lanes Blocked	$19.767 e^{0.4882x}$	0.9970	0.0017	12.9538
18	3	60	Shoulder	$0.0285 e^{5.7633x}$	0.8150	0.1278	8.2262
19	3	60	1 Lane Blocked	$10.036 x^{5.0181}$	0.9519	0.0004	7.1785
20	3	60	2 Lanes Blocked	$20.683 x^{2.0521}$	0.9935	0.0006	23.2591
21	4	15	Shoulder	$0.0414 e^{4.8981x}$	0.9530	0.0412	1.7301
22	4	15	1 Lane Blocked	$0.0233 e^{4.3598x}$	0.9987	0.0259	3.4693
23	4	15	2 Lanes Blocked	$1.2976 e^{0.9163x}$	0.9990	0.0041	2.6492
24	4	30	Shoulder	$0.031 e^{5.3075x}$	0.9341	0.0620	2.5715
25	4	30	1 Lane Blocked	$2.8649 x^{6.4143}$	0.9908	0.0082	4.9807
26	4	30	2 Lanes Blocked	$7.6089 e^{0.6761x}$	0.9941	0.0027	4.8779
27	4	45	Shoulder	$0.0212 e^{5.8451x}$	0.9063	0.0878	4.0554
28	4	45	1 Lane Blocked	$3.9051 x^{7.2473}$	0.9682	0.0043	6.8487
29	4	45	2 Lanes Blocked	$13.749 e^{0.7397x}$	0.9957	0.0032	12.3863
30	4	60	Shoulder	$0.0146 e^{6.3674x}$	0.8792	0.1089	6.0304
31	4	60	1 Lane Blocked	$4.9955 x^{8.0031}$	0.9488	0.0031	9.7989
32	4	60	2 Lanes Blocked	$24.686 x^{2.2331}$	0.9878	0.0012	20.1692
33	5	15	Shoulder	$0.0443 e^{4.9055x}$	0.9435	0.0439	1.6705
34	5	15	1 Lane Blocked	$0.0148 e^{5.0173x}$	0.9656	0.0421	3.5468
35	5	15	2 Lanes Blocked	$0.2984 e^{2.0305x}$	0.9959	0.0125	3.6757

Table B.1, continued

36	5	30	Shoulder	$0.0374 e^{5.1516x}$	0.9318	0.0571	2.1312
37	5	30	1 Lane Blocked	$0.0049 e^{6.4393x}$	0.9594	0.0276	6.2511
38	5	30	2 Lanes Blocked	$5.8554 x^{2.9402}$	0.9973	0.0011	3.1708
39	5	45	Shoulder	$0.0301 e^{5.4684x}$	0.9152	0.0741	2.8418
40	5	45	1 Lane Blocked	$4.6166 x^{7.798}$	0.9333	0.0199	9.4124
41	5	45	2 Lanes Blocked	$11.964 x^{2.9056}$	0.9960	0.0009	5.9141
42	5	60	Shoulder	$0.0234 e^{5.8313x}$	0.8953	0.0922	3.8367
43	5	60	1 Lane Blocked	$5.7617 x^{8.7629}$	0.9259	0.0188	14.6656
44	5	60	2 Lanes Blocked	$19.208 x^{3.1466}$	0.9902	0.0002	6.7798

Table B.2 – Urban Delay Models

Urban							
Model Number	**Lanes**	**Duration (min)**	**Severity**	**Equation**	**Trend Line R^2**	**P-Value of Variable**	**Standard Error**
45	2	15	Shoulder	$1.0057\ e^{1.9612x}$	0.8098	0.0677	1.8073
46	2	15	1 Lane Blocked	$1.4094\ e^{1.2185x}$	0.9953	0.0050	2.5887
47	2	30	Shoulder	$0.6229\ e^{2.6077x}$	0.7319	0.1094	3.7642
48	2	30	1 Lane Blocked	$2.6655\ e^{1.384\ x}$	0.9860	0.0156	12.0507
49	2	45	Shoulder	$0.3926\ e^{3.2306x}$	0.6845	0.1349	6.5682
50	2	45	1 Lane Blocked	$15.354\ x^{2.4909}$	0.9994	0.0009	7.4497
51	2	60	Shoulder	$0.2675\ e^{3.7515x}$	0.6500	0.1504	10.0753
52	2	60	1 Lane Blocked	$24.248\ x^{2.7779}$	0.9930	0.0002	9.5535
53	3	15	Shoulder	$0.5044\ e^{2.4111x}$	0.8372	0.0637	1.5163
54	3	15	1 Lane Blocked	$0.3437\ e^{2.2839x}$	0.9905	0.0165	3.2529
55	3	15	2 Lanes Blocked	$3.209\ e^{0.4832x}$	0.9977	0.0013	1.8671
56	3	30	Shoulder	$0.3269\ e^{3.0136x}$	0.7713	0.1008	2.8766
57	3	30	1 Lane Blocked	$5.1729\ x^{3.9196}$	0.9967	0.0023	3.9295
58	3	30	2 Lanes Blocked	$12.287\ e^{0.4207x}$	0.9778	0.0049	7.5983
59	3	45	Shoulder	$0.2021\ e^{3.6812x}$	0.7199	0.1290	5.1048
60	3	45	1 Lane Blocked	$7.835\ x^{4.3996}$	0.9748	0.0006	4.6985
61	3	45	2 Lanes Blocked	$20.948\ e^{0.4932}$	0.9898	0.0008	10.8861
62	3	60	Shoulder	$0.1345\ e^{4.2429x}$	0.6920	0.1441	7.7365
63	3	60	1 Lane Blocked	$10.917\ x^{4.8819}$	0.9562	0.0005	7.7823
64	3	60	2 Lanes Blocked	$19.925\ x^{2.1499}$	0.9862	0.0001	13.4607
65	4	15	Shoulder	$0.2474\ e^{3.0174}$	0.9064	0.0457	1.2611
66	4	15	1 Lane Blocked	$0.0891\ e^{3.4091x}$	0.9937	0.0271	3.1943
67	4	15	2 Lanes Blocked	$1.6222\ e^{0.8647x}$	0.9991	0.0031	2.4362
68	4	30	Shoulder	$0.1778\ e^{3.4842x}$	0.8606	0.0734	2.0850
69	4	30	1 Lane Blocked	$3.9857\ x^{5.4076}$	0.9988	0.0093	5.0784
70	4	30	2 Lanes Blocked	$7.2621\ e^{0.709x}$	0.9962	0.0022	4.9677
71	4	45	Shoulder	$0.1199\ e^{4.0404x}$	0.8136	0.1011	3.4224
72	4	45	1 Lane Blocked	$5.257\ x^{6.361}$	0.9865	0.0056	7.6130
73	4	45	2 Lanes Blocked	$12.547\ e^{0.7931x}$	0.9961	0.0017	11.1635
74	4	60	Shoulder	$0.0813\ e^{4.5901x}$	0.7768	0.1216	5.2498
75	4	60	1 Lane Blocked	$6.643\ x^{7.1851}$	0.9719	0.0042	11.3476
76	4	60	2 Lanes Blocked	$19.537\ x^{2.5227}$	0.9917	0.0000	5.8810
77	5	15	Shoulder	$0.2643\ e^{2.9606x}$	0.8816	0.0526	1.2291
78	5	15	1 Lane Blocked	$0.0731\ e^{3.7605x}$	0.9432	0.0482	3.3186
79	5	15	2 Lanes Blocked	$0.4731\ e^{1.81x}$	0.9960	0.0097	3.1273
80	5	30	Shoulder	$0.2166\ e^{3.2508x}$	0.8516	0.0712	1.6902

Table B.2, continued

81	5	30	1 Lane Blocked	$0.023\ e^{5.2249x}$	0.9627	0.0303	6.1528
82	5	30	2 Lanes Blocked	$6.1435\ x^{2.9175}$	0.9990	0.0014	3.5844
83	5	45	Shoulder	$0.1685\ e^{3.6167x}$	0.8171	0.0925	2.4026
84	5	45	1 Lane Blocked	$0.0098\ e^{6.3267x}$	0.9537	0.0224	9.7345
85	5	45	2 Lanes Blocked	$11.765\ x^{2.9978}$	0.9977	0.0012	7.0007
86	5	60	Shoulder	$0.1282\ e^{4.0148x}$	0.7843	0.1120	3.3772
87	5	60	1 Lane Blocked	$0.0048\ e^{7.2413x}$	0.9439	0.0209	15.2376
88	5	60	2 Lanes Blocked	$18.61\ x^{3.269}$	0.9925	0.0004	9.2197

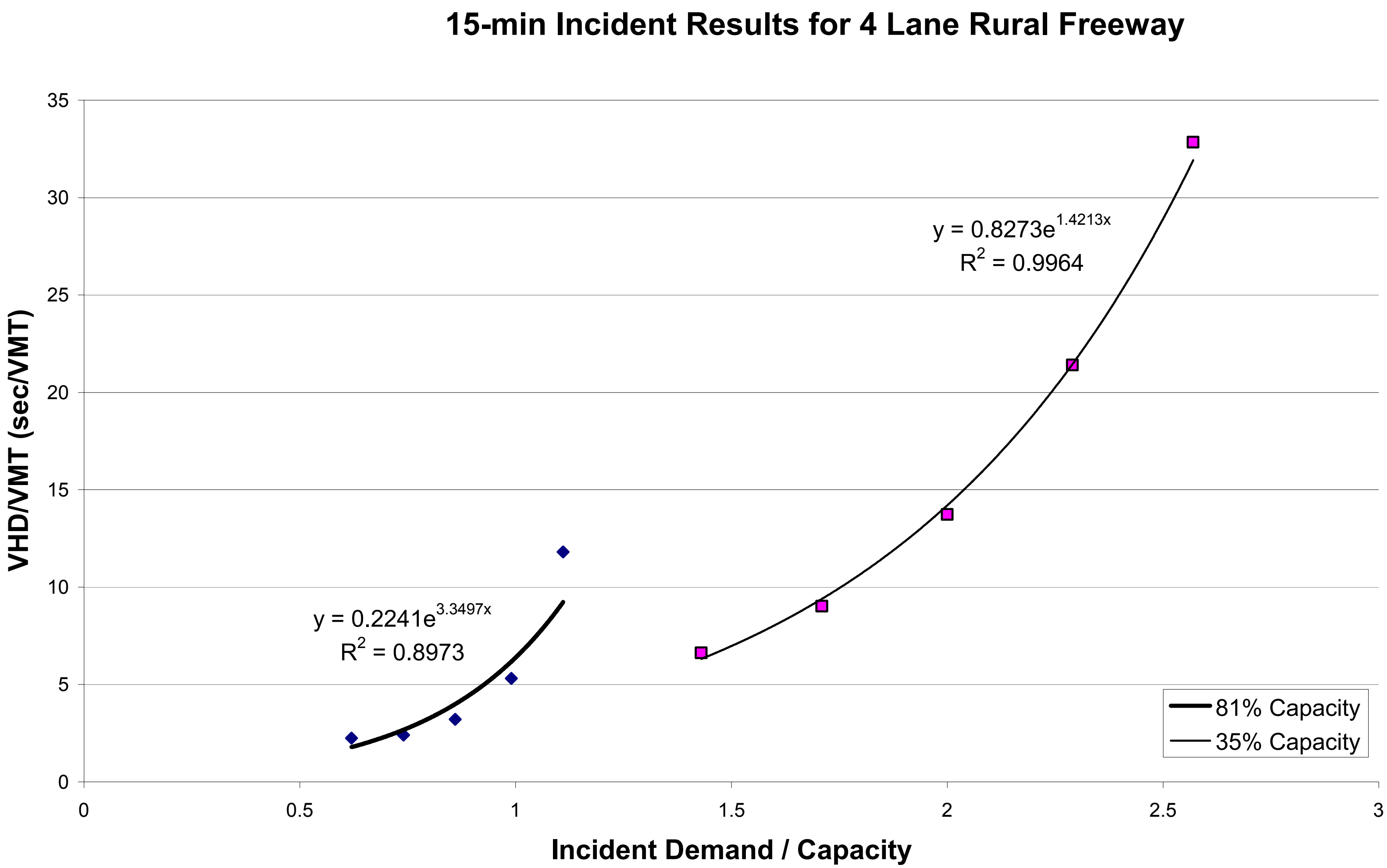

Figure B.1 –Rural Facility Delay Rate Models for 4 Lane and Indicated Available % Capacities

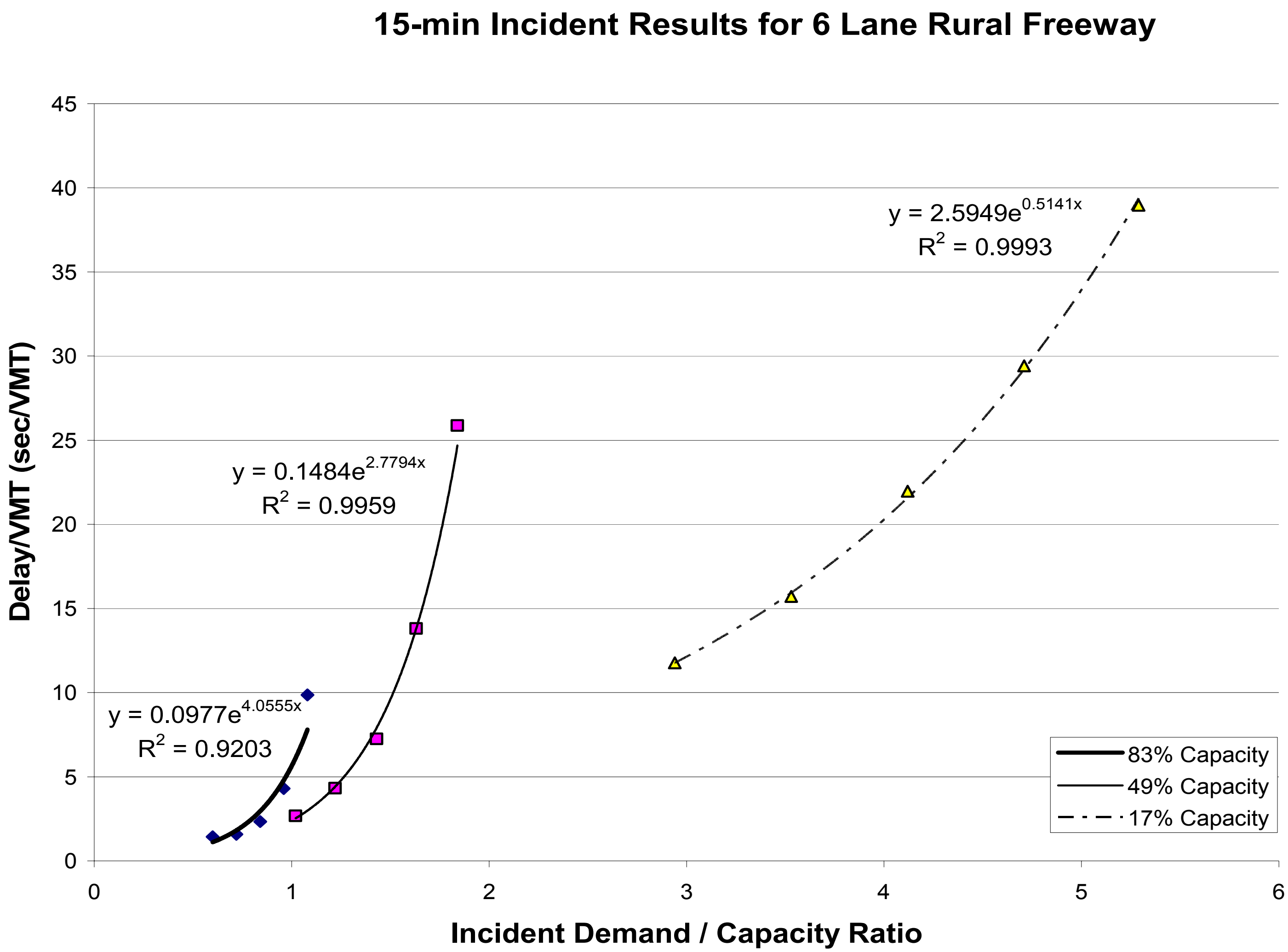

Figure B.2 –Rural Facility Delay Rate Models for 6 Lane and Indicated Available % Capacities

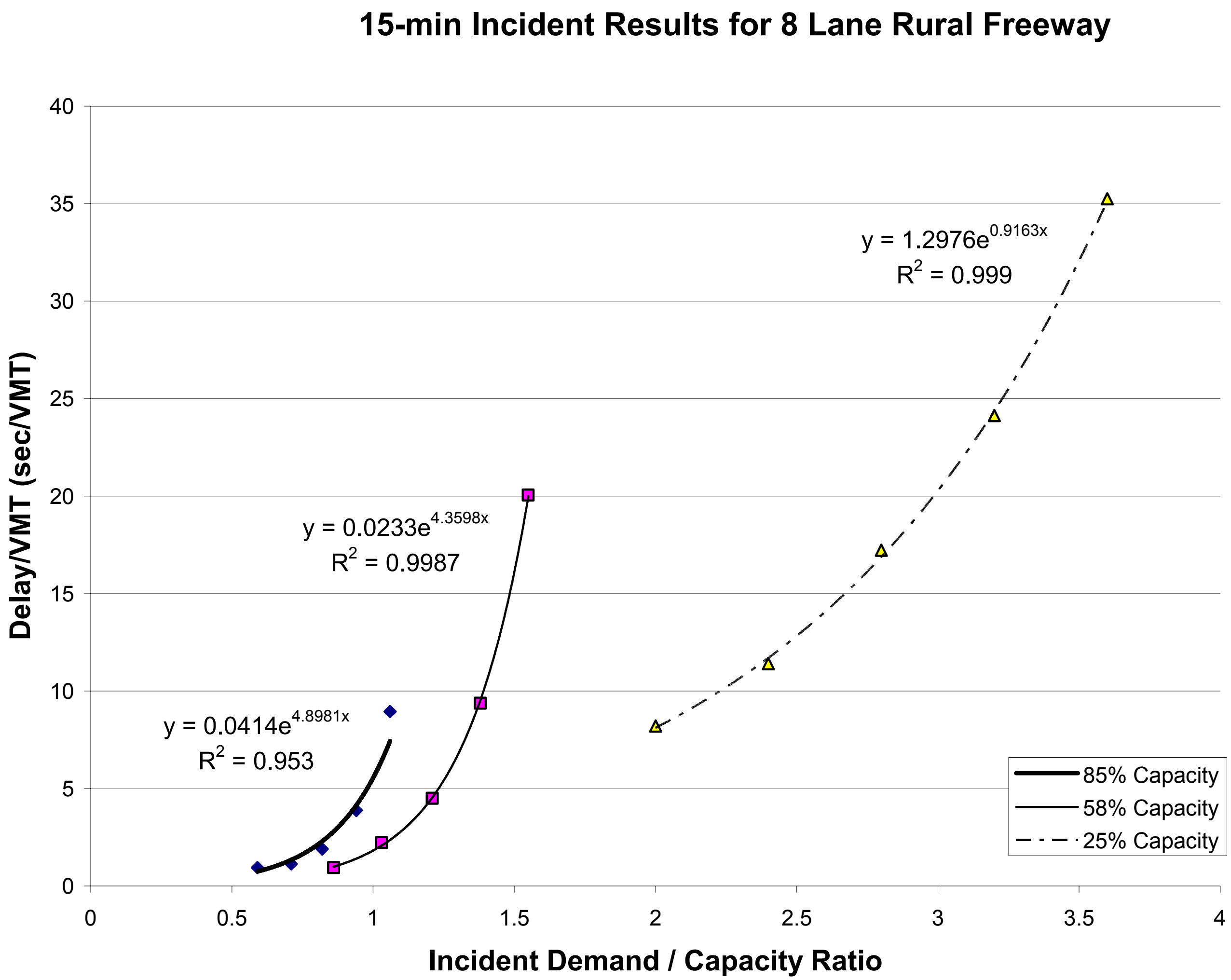

Figure B.3 –Rural Facility Delay Rate Models for 8 Lane and Indicated Available % Capacities

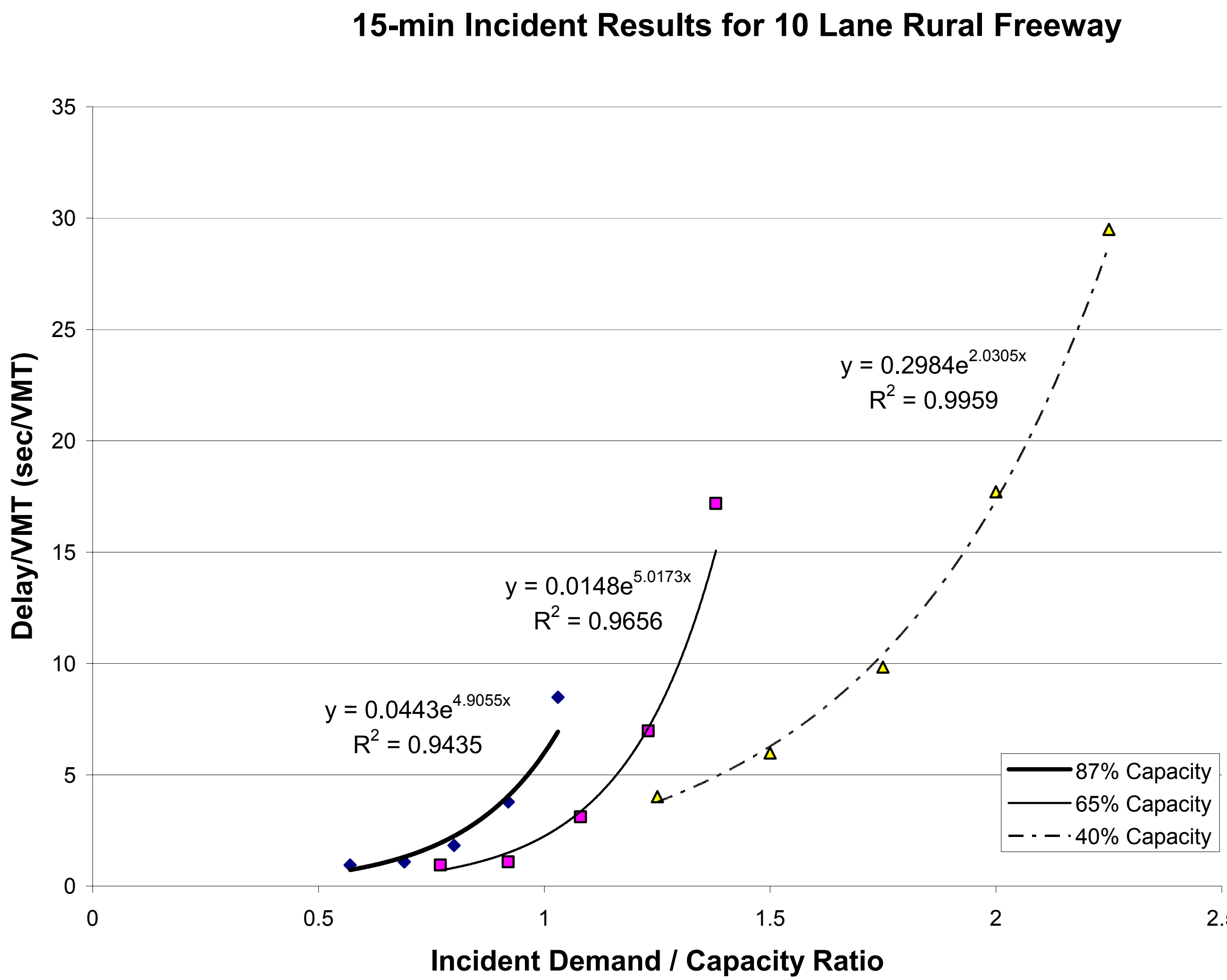

Figure B.4 –Rural Facility Delay Rate Models for 10 Lane and Indicated Available % Capacities

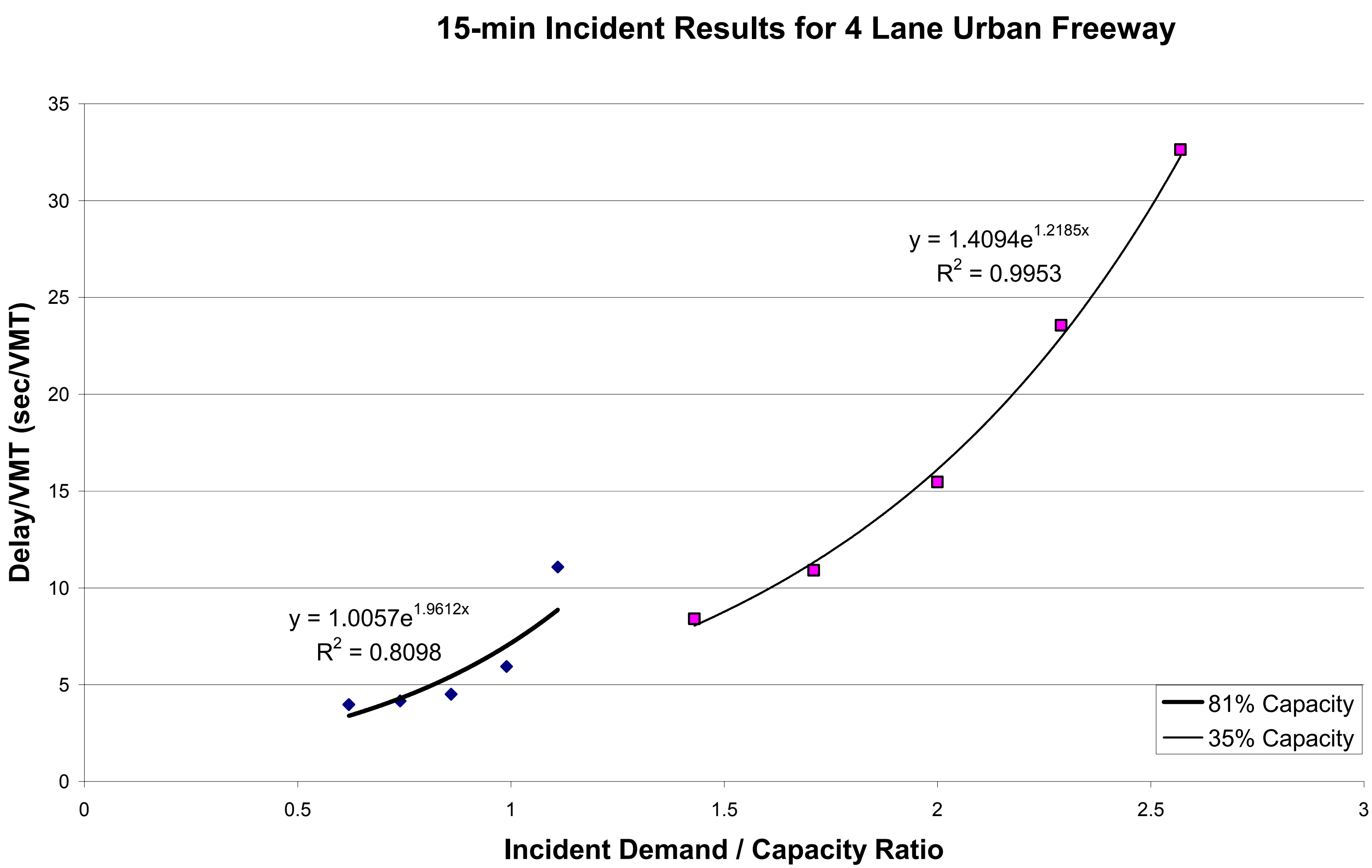

Figure B.5 –Urban Facility Delay Rate Models for 4 Lane and Indicated Available % Capacities

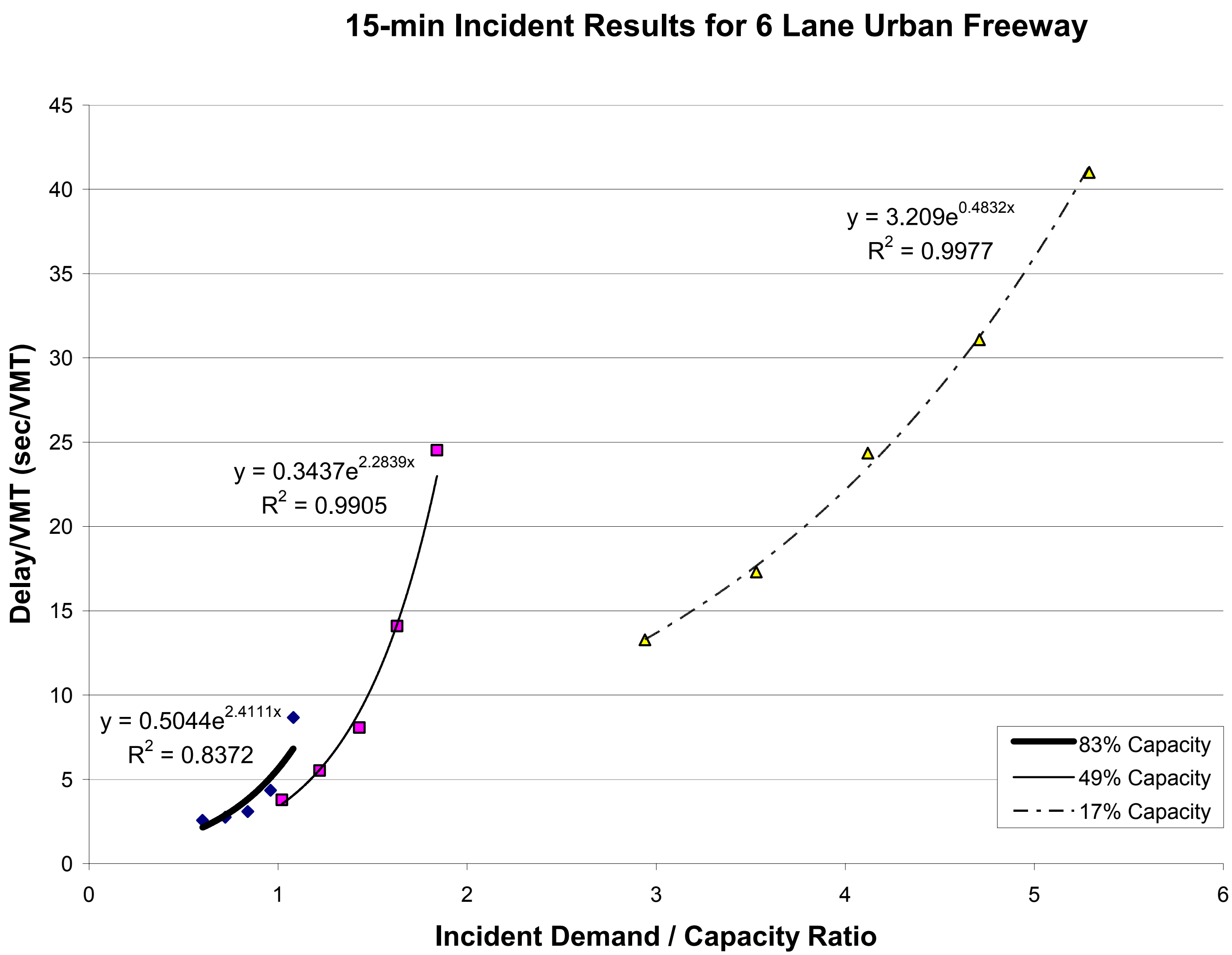

Figure B.6 –Urban Facility Delay Rate Models for 6 Lane and Indicated Available % Capacities

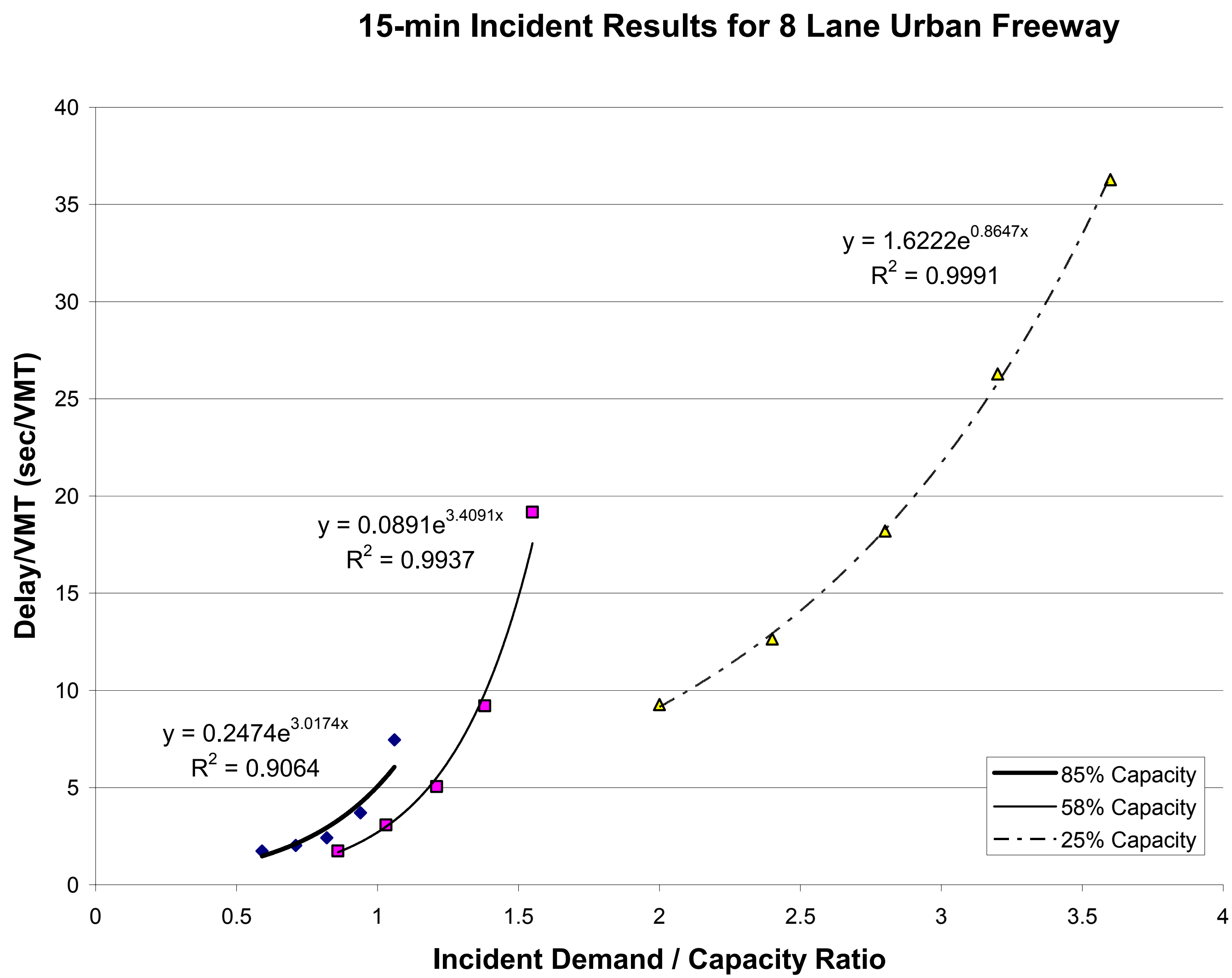

Figure B.7 –Urban Facility Delay Rate Models for 8 Lane and Indicated Available % Capacities

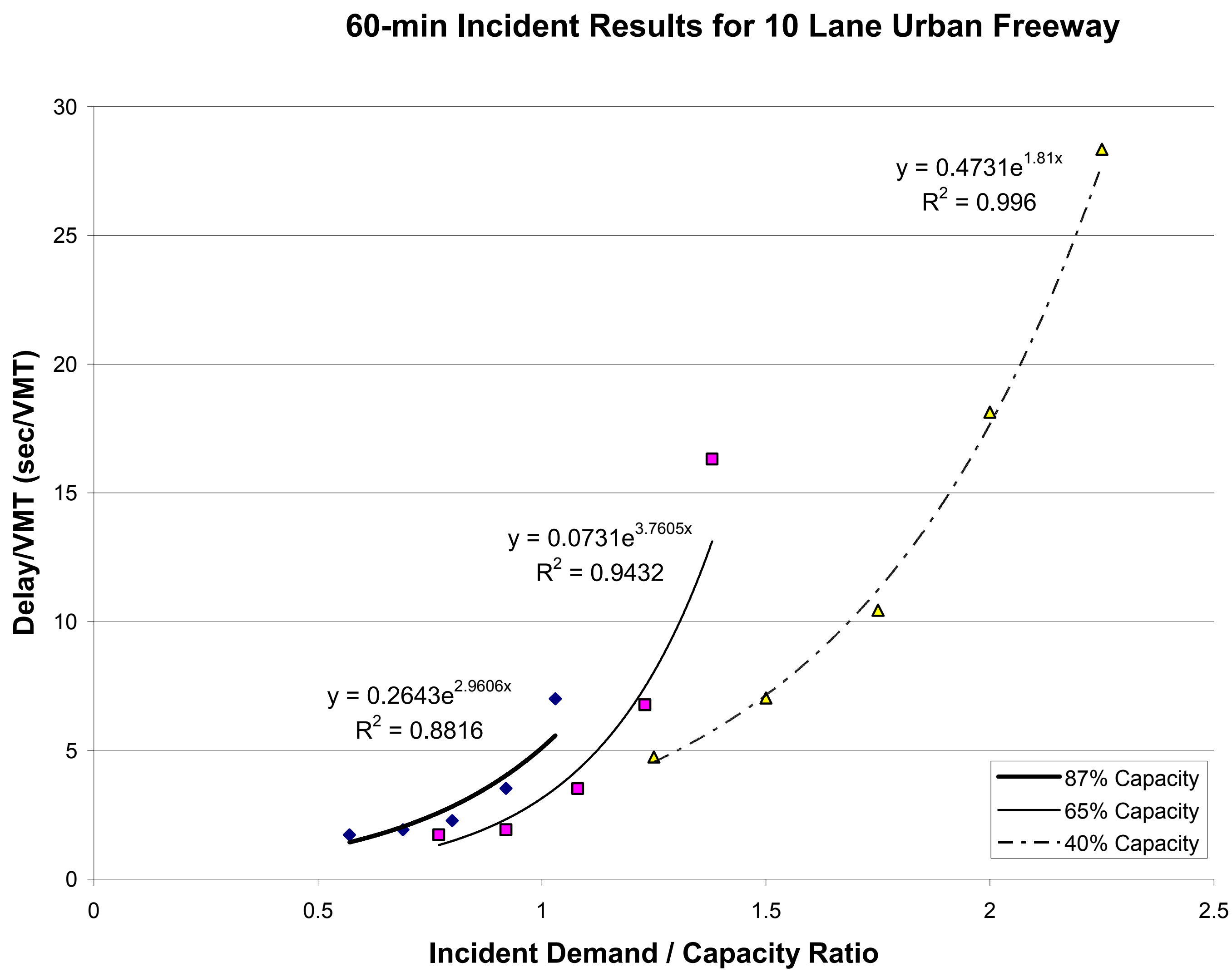

Figure B.8 –Urban Facility Delay Rate Models for 10 Lane and Indicated Available % Capacities

APPENDIX C – ANALYSIS TABLES

Table C.1 – Measures of Performance: Percentile Distributions (*28*)

	AADT per Lane			**Crashes per Mile per Year**			**Crashes per 100 Million Vehicle Miles**		
Percentiles	All Sites	Non-FSP Sites	FSP Sites	All Sites	Non-FSP Sites	FSP Sites	All Sites	Non-FSP Sites	FSP Sites
95	19163	14407	22388	84.8	53.6	138.0	395	375	416
90	16677	12769	20000	53.1	30.3	78.0	237	211	259
85	15370	11500	19000	36.8	19.0	63.1	167	144	204
80	14000	10805	17900	27.4	14.6	48.8	134	112	164
75	13000	10250	16674	20.0	11.1	40.3	110	95	143
70	12167	9996	15825	16.7	9.5	33.3	96	84	116
65	11256	9250	15500	13.7	8.3	28.6	84	72	105
60	10750	8750	14625	11.1	7.0	24.2	73	63	95
55	10250	7996	14000	9.5	6.1	20.5	65	58	83
50	9750	7500	13500	8.3	5.4	18.5	58	51	74
45	9167	7000	12667	6.9	4.8	16.1	52	45	67
40	8474	6285	12333	5.9	4.2	14.3	45	42	59
35	7596	5838	12000	5.0	3.5	12.5	41	38	52
30	6833	5238	11107	4.3	2.9	10.5	37	34	44
25	6136	4842	10750	3.5	2.3	9.0	33	28	40
20	5309	4394	10500	2.6	1.8	7.6	26	21	35
15	4719	3686	10000	1.8	0.9	6.0	18	9	29
10	3719	3279	9167	0.0	0.0	4.5	0	0	24
5	3039	2450	7330	0.0	0.0	0.6	0	0	3

Note: The above numbers are based on 1997-1999 statewide crash and inventory data.

Table C.2 – Response Distance Simulation Results

Number of Trucks	Length (N_{TS})	Average Distance (N_{TS})
1	5	2.500000
	6	2.861111
	7	3.214286
	8	3.562500
	9	3.907407
	10	4.250000
	11	4.590909
	12	4.930556
	13	5.269231
	14	5.607143
	15	5.944444
2	5	1.617778
	6	1.881313
	7	2.130298
	8	2.369792
	9	2.602760
	10	2.831053
	11	3.055884
	12	3.278080
	13	3.498225
	14	3.716742
	15	3.933946
3	5	1.153333
	6	1.374242
	7	1.578100
	8	1.770313
	9	1.954248
	10	2.132105
	11	2.305372
	12	2.475091
	13	2.642012
	14	2.806689
	15	2.969540
4	5	0.849524
	6	1.047475
	7	1.227344
	8	1.394505
	9	1.552360
	10	1.703240
	11	1.848754
	12	1.990064
	13	2.128016
	14	2.263251
	15	2.396254

Note: N_{TS} = Number of turnaround spacings