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Foreword

Inclement weather has significant impacts on transportation system. For example, studies have shown reductions in roadway capacity, increased drivers' response and reaction times, reductions in travel demands, etc. during inclement weather. Studies have also shown that incorporating inclement weather into transportation operations and managements could improve transportation system performances.

This document is developed to guide traffic engineers and transportation operations managers in analyzing and modeling weather impacts on transportation system. It is expected that by utilizing the weather module, better estimates and predictions of real world traffic parameters during inclement weather conditions can be made, leading to appropriate measures for improving highway safety and mobility in inclement weather.

This document serves as Volume XI in the FHWA Traffic Analysis Toolbox. Preceding volumes in the toolbox include: *Volume I: Traffic Analysis Tools Primer, Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools, Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software, Volume IV: Guidelines for Applying CORSIM Microsimulation Modeling Software, Volume V: Traffic Analysis Tools Case Studies - Benefits and Best Practices, Volume VI: Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness, Volume VII: Predicting Performance with Traffic Analysis Tools: Case Studies, Volume VIII: Work Zone Modeling and Simulation—A Guide for Decision-Makers*, *Volume IX: Work Zone Modeling and Simulation – A Guide for Analysis,* and *Volume X: Localized Bottleneck Congestion Analysis Focusing on What Analysis Tools Are Available, Necessary and Productive for Localized Congestion Remediation*.

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16. Abstract

This document presents a weather module for the traffic analysis tools program. It provides traffic engineers, transportation modelers and decisions makers with a guide that can incorporate weather impacts into transportation system analysis and modeling. The module describes how users can implement weather analysis using mesoscopic or microscopic traffic simulation modeling tools. It also includes weather and traffic data sources and discusses various weather responsive traffic operations and management strategies.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	$(F - 32) \div 1.8$	Celcius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celcius	$1.8C + 32$	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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Introduction and Purpose

We live in a part of the world where inclement weather conditions occur, affecting traffic operations. Traffic behaves differently when inclement weather is thrown into the mix, and to say that traffic will always be affected in one particular way is not true because there are various types of inclement weather. This weather module was developed as part of FHWA's Traffic Analysis Tools (TAT) program to guide traffic engineers and transportation operations managers in analyzing and modeling weather impacts on highway traffic movement. Users of this TAT weather module will learn how to calibrate traffic stream parameters (e.g., free flow speed, speed at capacity, and saturation flow at capacity) based on weather-related parameters (e.g., precipitation type, precipitation intensity level, and visibility). By utilizing the weather module, better estimates and predictions of real world traffic parameters during inclement weather conditions can be made, leading to appropriate measures for improving highway safety and mobility in inclement weather.

The purpose of the weather TAT module is to provide Traffic Management Center (TMC) operators and traffic engineers with practical guidance for implementing proper traffic operational strategies specific to inclement weather conditions.

Traffic Analysis Toolbox Volume XI includes six chapters. The following provides a brief description of each chapter.

Chapter 1, entitled "Why Weather?", presents a brief overview of the topics covered in this TAT weather module. Topics included in Chapter 1 include: weather impacts on the transportation system, the available traffic analysis and modeling tools that incorporate those impacts, and the benefits of incorporating weather analysis into traffic operations and management strategies.

Chapter 2 elaborates on the discussion of weather impacts on the transportation system. Examples of these weather impacts are given on two traffic analysis levels: the macroscopic level and the microscopic level. The macroscopic level impacts discussed in this chapter include the weather impacts on traffic stream parameters, such as capacity, volume and speed at capacity, for an aggregated group of vehicles. The section on microscopic-level impacts addresses weather impacts on traffic parameters that correlate with the individual vehicular movements (e.g., lost startup time and saturation headway).

Chapter 3 starts with a brief overview of the three main types of traffic analysis tools (i.e., macroscopic, mesoscopic, and microscopic) that describes the capabilities and limitations for each type of tool. It then provides procedures for conducting weather-related traffic analyses using mesoscopic and microscopic traffic simulation tools (note that macroscopic tools are not considered as they have not been employed in weather impact analysis).

Chapter 4 presents examples of available weather, traffic, and Intelligent Transportation Systems (ITS) data sources that can be used to conduct a weather-related traffic analysis. Discussions of *Clarus*, the Highway Performance Monitoring System, and the connected vehicles initiative are included in this chapter.

Chapter 5 discusses on Weather Responsive Traffic Management (WRTM) Concept of Operations and existing traffic management strategies that would benefit from weather impact analysis.

Finally, Chapter 6 provides two case studies that were conducted to analyze weather impacts on traffic operations using mesoscopic and microscopic traffic modeling tools. In the first case study, DYNASMART-P, a mesoscopic traffic modeling tool, was used to develop models that estimated and predicted inclement weather impacts on freeway segments in the Hampton Roads region of Virginia. The second case study used two microscopic traffic modeling tools, CORSIM and SimTraffic, to evaluate weather-specific signal timing plans for four New England corridors.

1.0 Why Weather?

Weather conditions—consisting of rain, fog, snow, wind, and extreme temperatures—affect traffic operations and safety for a significant portion of the year in the United States. About 24 percent of all crashes in the United States are weather-related, resulting in more than 673,000 injuries and about 7,400 fatalities each year (Pisano *et al*., 2009). Inclement weather impacts roadway surface conditions and driver behavior, which result in increased delays and crash risks. Information about these impacts is widely available from past literature and recent studies, but this knowledge has not been fully incorporated into current traffic analysis tools. Because weather has significant effects on the transportation system, it should be taken into consideration when analyzing traffic operations. This section briefly discusses the impacts inclement weather conditions have on the transportation system, the available traffic analysis and modeling tools that incorporate those impacts, and the benefits of incorporating weather into traffic operations and management strategies.

Traffic conditions are usually at their best in ideal weather. Such conditions are defined by the following characteristics: dry roadway, good visibility (greater than 0.25 miles), no precipitation, and winds less than 9.94 mph (Zhang *et al*., 2004). Of course the ideal weather condition is not guaranteed every time a trip is made on the road. A chain effect occurs when weather is involved: a weather event changes roadway conditions (e.g., reduced visibility and pavement friction), which leads to a reduction in traffic supply parameters (e.g., lower free-flow speeds and capacities), which in turn affect traffic flow (e.g., higher delays and lower average speeds).

A significant indicator of the effects of inclement weather on the transportation system is traffic demand. This is the volume of traffic that is seen daily, or the number of drivers that use the traffic facility. In most cases, not including commuter traffic, inclement weather indirectly correlates with traffic demand. As the severity of adverse weather increases, traffic demand tends to decrease. In a study conducted on I-35 in northern rural Iowa, researchers extracted traffic counts for several snowy days that received more than 1 inch of snow in 24 hours. The study presented the following results: I-35 experienced a 20 percent reduction in traffic volumes on snowy days with low wind speed and good visibility, and an 80 percent reduction in traffic volumes on snowy days with high wind speed (as high as 40 mph) and poor visibility (less than one-quarter of a mile) (Maze *et al*., 2005).

The occurrence of inclement weather conditions may be more significant for some cities in the United States. According to Kyte *et al*. (2001), the National Weather Service provides records of rain days for 284 sites in the United States for at least 10 years; these records show that nearly one-third of the sites have rainy days that occur about 34 percent of the year and 15 percent of the sites have rainy days occurring 41 percent of the year. Potential traffic impacts such as side-swipe crashes, t-bone crashes, and rear impact crashes may be attributed to impaired visibility and reduced road surface friction due to the frequency and intensity of rain. If rainfall occurs for a significant portion of the year for some of these sites then it will be beneficial for traffic engineers to incorporate the impact of inclement weather into their capacity and level of service analyses.

Many studies have shown the impacts of weather on traffic, depending on the severity of rain, snow, or other conditions. In addition, researchers have already incorporated such weather impacts in analyses using traffic simulation modeling tools, such as DYNASMART, DynaMIT,

AIMSUN, CORSIM, INTEGRATION, PARAMICS, VISSIM, etc. Adjustable weather factors allow these model tools to simulate realistic traffic situations in inclement weather. Furthermore, weather databases provide adequate weather data to deploy the weather module for traffic operations and management.

Weather data sources, such as *Clarus*, can be used by traffic engineers as a means of incorporating inclement weather impacts into existing traffic analysis tools. *Clarus* is designed to display current and forecasted weather-related data for a particular region. Its main goal is to decrease the effects of inclement weather on all road and transit users and operators. With *Clarus*, current users can obtain weather-related data for 38 States in the United States and 3 provinces in Canada that uses a common format.

The connected vehicles initiative could be an essential tool in making inclement weather information networks and the transportation system a more cohesive unit. Connected vehicles, a US Department of Transportation initiative, is designed to create a network that connects vehicles to infrastructure and wireless devices. It is proposed that connecting these three elements will enhance safety and mobility and reduce the negative effects of transportation on the environment.

Steps have been taken by transportation agencies to incorporate weather into traffic operation and management strategies. Current weather-responsive traffic operation and management strategies range widely from motorist advisory (alert and warning systems) to traffic signal control strategies, all of which are used to facilitate travel in inclement weather. Motorist advisory, alert, and warning systems make drivers more aware of current and impending weather and pavement conditions through passive warning systems, active warning systems, en-route weather alerts, pre-trip road condition information, and pavement condition information (Batelle *et al*., 2010). A survey showed that about 92 percent of respondents would slow down if the high wind warning was activated (Kumar and Strong, 2006). In traffic signal control strategies, traffic signals are modified to optimize traffic operations during inclement weather. This may be performed by changing the interaction between detection systems and traffic signal control systems, implementing weather specific traffic signal timing plans, or programming weather-responsive ramp metering timing parameters. Traffic operation and management strategies that incorporate the results from weather responsive traffic analyses have the potential to provide operational benefits. These results can inform, support, and improve advisory strategies, control strategies, and treatment strategies.

2.0 Weather Impacts on the Transportation System

It is generally understood that weather events affect roadway and traffic operations. FHWA summarized such impacts under various weather events as shown in Table 2-1.

Table 2-1 Weather Impacts on Roadways and Traffic Operations

Weather Events	Primary Roadway Impacts	Primary Traffic Operation Impacts
Rain, Snow, Ice, Sleet, Hail & Flooding	Reduced pavement friction Lane obstruction & submersion Reduced visibility Infrastructure damage	Reduced roadway capacity and speed Increased delay and speed variance Increased crash risk Road restrictions & closures
Strong Winds	Reduced visibility due to blowing snow/dust Lane obstruction due to wind-blown debris & drifting snow Reduced vehicle performance	Increased delay Reduced traffic speeds Increased crash risk Bridge restrictions & closures
Fog, Smog & Smoke	Reduced visibility	Reduced speeds & increased delay Increased speed variability Increased crash risk
Lightning & Extreme Temperatures	Infrastructure damage	Traffic control device failure Loss of power/communications services

Rain substantially impacts drivers, vehicles, and roadways. Accumulated water on the roadway can greatly decrease the friction between the treads of a tire and the roadway surface. In addition, visibility is reduced to a poor quality due to raindrops falling onto the windshields of vehicles and by water that is dispersed upward from the roadway surface by the tires of nearby vehicles. In these conditions, it is not uncommon to find reductions in capacity and speed at capacity. For example, a study by Rakha *et al*. (2008) showed rainfall reduced capacity by 10-11 percent.

Like rain, snowy conditions affect the operations of the transportation system. Snow reduces the roadway surface friction, making traveling difficult. Due to reduced roadway friction, drivers tend to decrease their traveling speeds which cause headway to increase and saturation flow to decrease. Perrin *et al*. (2001) and Agbolosu-Amison *et al*. (2004) conducted studies to analyze the impacts of snowy conditions on traffic flow, which included lower speeds and saturation flow rates. These studies show that the maximum reduction of saturation flow rate was 21 percent for snowy conditions.

2.1. Macroscopic Level Impacts

Inclement weather conditions affect the transportation system on a macroscopic level. Table 2-2 presents the impacts of rain and snow on macroscopic parameters typically analyzed in traffic operations.

Table 2-2 Macroscopic Level Impacts on Traffic Operations

Typical Impacts	Weather Event	
	Rain	Snow
Capacity	-4 ~ −30%	−3 ~ −27%
Volume	−20%	−6 ~ −26%
Speed at Capacity	−8 ~ −14%	−5 ~ −19%
Saturation Flow	−2 ~ −6%	−4 ~ −21%

(Sources: Agbolosu-Amison *et al*., 2004; Dalta and Sharma, 2008; Prevedourous and Chang, 2004; Rakha *et al*., 2008; Samba and Park, 2009)

These impacts vary by time-of-day and day-of-week. Generally, traffic flow during daytime peak hours is much heavier than daytime off-peak hours. Dalta and Sharma (2008) indicated that commuter roads obtained lower reductions in traffic volume during daytime peak hours (-6 to 10 percent) than during daytime off-peak hours (-10 to -15 percent). This may be attributable to the larger number of work-related trips (necessary trips) made during these peak hours.

Inclement weather also impacts speed at capacity. A recent study conducted by Rakha *et al.* (2008) shows reductions in speed at capacity for varying intensities of rain and snow. Maximum reductions ranged from 8 to 14 percent and 5 to 19 percent for rainy and snowy conditions, respectively. Reductions are due to weather-related roadway impacts such as reduced visibility and lower roadway surface friction.

2.2. Microscopic Level Impacts

Inclement weather increases lost startup time, increases saturation headway, and reduces free-flow speed, ultimately affecting the flow of traffic. The decline in traffic flow volumes during inclement weather conditions is noticeable on time-sensitive facilities such as signalized intersections, where fewer vehicles travel through the green phase of an intersection approach because the signal timing is not adjusted to accommodate inclement weather conditions. Table 2-3 presents the microscopic traffic impacts typically observed in inclement weather conditions.

Table 2-3 Microscopic Level Impacts on Traffic Operations

Typical Impacts	Weather Event	
	Rain	Snow
Lost startup time	+7.6 ~ 31.5%	+18.5 ~ 65.2%
Saturation Headway	+2.5 ~ 13.2%	+4.4 ~ 30.9%
Free-Flow Speed	−2 ~ −9%	−3 ~ 36%

(Sources: Agbolosu-Amison *et al*., 2004; Perrin *et al*., 2001)

Roadway surface quality degrades significantly under severe snowy conditions. When snow accumulates on roadways, vehicles have less tire traction, ultimately causing initial movements to stall. These conditions lead to slower startup times for vehicles. For example, due to inclement weather, lost startup times increased by an average of 23 percent (Perrin *et al*., 2001) and saturation headways also increased by a maximum of 30.9 percent (Agbolosu-Amison *et al*., 2004).

Drivers' reducing their speeds during heavy rain or snow is a clear indication that inclement weather affects driver behavior. The more severe the inclement weather condition, the more likely drivers are to adjust their behavior behind the wheel to accommodate their comfort levels. For example, drivers respond to poor environmental conditions (e.g., low visibility and high

winds) by reducing their free flow speeds. One study found that free-flow speeds for all vehicles decreased by 7.5 percent and 18.1 percent during foggy and snowy conditions, respectively (Liang *et al*., 1998).

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3.0 Traffic Analysis Tools Incorporating Weather

3.1. Overview

One universally correct method to conduct traffic analyses cannot exist due to the fact that all traffic analyses do not share the same objectives. Objectives are an important deciding factor in choosing a type of traffic analysis. For instance, if a study's objective is to simulate traffic flow for multiple regions of a State, analysts need to choose a traffic analysis tool that can handle the amount of data that is involved in the study. The three main types of analysis are: macroscopic analysis, mesoscopic analysis, and microscopic analysis. This section defines each analysis type and discusses their modeling capabilities and limitations.

3.1.1. Macroscopic Analysis

If there is one thing to take away from learning about transportation operations, it is that flow, speed, and density are all related to each other. The conditions of two will affect the third traffic stream parameter. For instance, if drivers on a highway are able to travel at their free-flow speeds and maximum density has not been reached, then the flow of traffic will run smoothly. When users incorporate macroscopic simulation models into their traffic analyses, they are analyzing the relationship among the three traffic stream parameters.

When we consider the word "macroscopic," we think "large scale." Accordingly, a key feature of most macroscopic models is their ability to model large study areas. Using the flows, speeds, and density measures of a large network, macroscopic models can provide simple representations of the traffic behavior in that network. Because these models do not require detailed data such as driver characteristics, model set up can be done quickly and the simulation can output results in a timely manner (*Traffic Analysis Toolbox Volume I* – Alexiadis *et al*., 2004).

Although the ability of macroscopic models to output a simple representation of traffic flow in a timely manner is considered a benefit, it is considered a limitation as well. Macroscopic models can simulate traffic stream parameters (i.e., flow, speed, and density) on a large scope, but they cannot model detailed behavior in individual vehicle movements (e.g., saturation headway and lost startup time).

The FHWA Traffic Analysis Toolbox lists the commonly used macroscopic simulation models and can be found at the following link:

- FHWA Traffic Analysis Tools – Macroscopic Simulation Models
  http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol1/sectapp_a.htm#a5

Note that no literature was found in the weather-related analysis using macroscopic modeling. This is because weather impacts cannot be effectively analyzed using macroscopic tools. As a result, this chapter does not discuss incorporating weather in macroscopic analysis.

3.1.2. Mesoscopic Analysis

Macroscopic models can only provide so much detail in simulating real world traffic conditions. In some cases, research requires more in-depth simulation results. This is where mesoscopic models come into play. These models have the ability to model large study areas but they provide users with more detailed information than macroscopic models.

More detailed traffic scenarios can be modeled using mesoscopic simulation models. For instance, users have the capability to model diversion routes from major roadways (e.g., freeways and highways) to other road types (e.g., signalized arterial). This could not be accomplished using macroscopic models.

With these capabilities come weaknesses. One key limitation in using mesoscopic models is the inability to model detailed operational strategies such as a coordinated traffic network. This operational strategy involves programming the traffic signals at several intersections so that the flow of traffic is optimized (i.e., drivers do not receive a red signal at each intersection they approach). Such an operation would be better suited in a microscopic model because it would require more detailed data. Mesoscopic models provide users with higher accuracy in simulating real world traffic behavior than macroscopic models, but microscopic models simulate real world traffic behavior with higher accuracy than mesoscopic models.

Commonly used mesoscopic simulation models include those from the DYNASMART and DYNAMIT family. Recent studies of inclement weather impacts on the transportation system have incorporated mesoscopic analysis with these models. The FHWA Traffic Analysis Toolbox provides additional information on mesoscopic simulation models at the following link:

- FHWA Traffic Analysis Tools – Mesoscopic Simulation Models
  http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol1/sectapp_a.htm#a6

3.1.3. Microscopic Analysis

When research requires heavily detailed analysis of real world traffic behavior, users would use microscopic simulation models. These models are intended to simulate the movement of individual vehicles, which can be done by using car-following models, longitudinal motion models (e.g., acceleration and deceleration models), gap-acceptance models, and lane-changing models.

Microscopic models allow users to simulate the stochastic nature of traffic. The drivers that you share the road with are not going to drive in the same manner as you. Their thinking patterns and comfort levels will vary for each traffic scenario presented to them. Incorporating driver behavior data is essential to simulate traffic conditions with the highest accuracy.

The ability of microscopic models to simulate traffic behavior with high accuracy is a benefit but also a weakness. In order to gain such a high level of accuracy, microscopic simulation models require substantial amounts of roadway geometry, traffic control, traffic pattern, and driver behavior data. Providing this amount of data will limit users to modeling smaller networks than those that can be modeled in macroscopic and mesoscopic analyses. The required input data will also cause each simulation run to take a very long time to output results.

The FHWA Traffic Analysis Toolbox lists commonly used microscopic simulation models. These include: CORSIM, VISSIM, AIMSUN, and PARAMICS. For additional information on microscopic simulation tools please refer to the following sites:

- FHWA Traffic Analysis Tools – Microscopic Simulation Models
  http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol1/sectapp_a.htm#a7
- Traffic Analysis Toolbox Volume IV: Guidelines for Applying CORSIM Microsimulation Modeling Software
  http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol4/vol4_guidelines.pdf

3.2. Mesoscopic Analysis

As noted, this chapter does not cover macroscopic analysis as weather impacts cannot be effectively analyzed using macroscopic tools.

Mesoscopic analysis is an emerging method for simulating and studying traffic. As explained in the 3.1 overview section, macroscopic simulation is a highly aggregated method for analyzing traffic that assumes all vehicles on the roadway have the same characteristics. However, this method is not appropriate to predict and understand changes happening at the vehicular level. Microscopic analysis looks at every individual vehicle and its unique characteristics. This method makes identifying changes and conflicts among vehicles easier; however, it requires a great deal of computing power and is most effective in smaller geographic networks.

One advantage of mesoscopic analysis is the ability to analyze larger geographic areas than microscopic analysis while still providing some of the detailed data that macroscopic analysis cannot provide. Mesoscopic analysis also allows for the analysis of road segments, multiple routes within a network, basic signalized intersections, freeways and ramps.

The major disadvantage to mesoscopic analysis is the heavy data requirement. Mesoscopic analysis requires almost as much data as microscopic simulation and for large geographic regions the data requirements are comparable to those of transportation planning studies. Another disadvantage to mesoscopic analysis is that some complex traffic features currently cannot be simulated well, such as sophisticated traffic signals.

3.2.1. Mesoscopic Traffic Simulation Model Setup

There are a number of software packages available for mesoscopic traffic modeling. In the United States, the more commonly used software are the Traffic Estimation and Prediction Systems (TrEPS) tools, formerly known as Dynamic Traffic Assignment (DTA) tools. These tools include DynaMIT-P, DynaMIT-X, DYNASMART-P, DYNASMART-X, and DynusT. Some other mesoscopic tools are listed below. This TAT module focuses primarily on TrEPS tools.

Mesoscopic Traffic Simulation Software Options
▪ CONTRAM (Continuous Traffic Assignment Model) http://www.contram.com ▪ DYNAMIT-P, DYNAMIT-X, DYNASMART-P, DYNASMART-X, DynusT: http://www.dynamictrafficassignment.org ▪ VISTA (Visual Interactive System for Transport Algorithms) http://www.vistatransport.com/ (revision date June 18, 2009)

(Source: *Traffic Analysis Toolbox Volume II* – Jeannotte *et al*., 2004)

A typical network in any of these programs might look something like Figure 3-1. It clearly shows the extent of the geographic area that this model can analyze: an area much larger than a typical microscopic simulation would be able to handle.

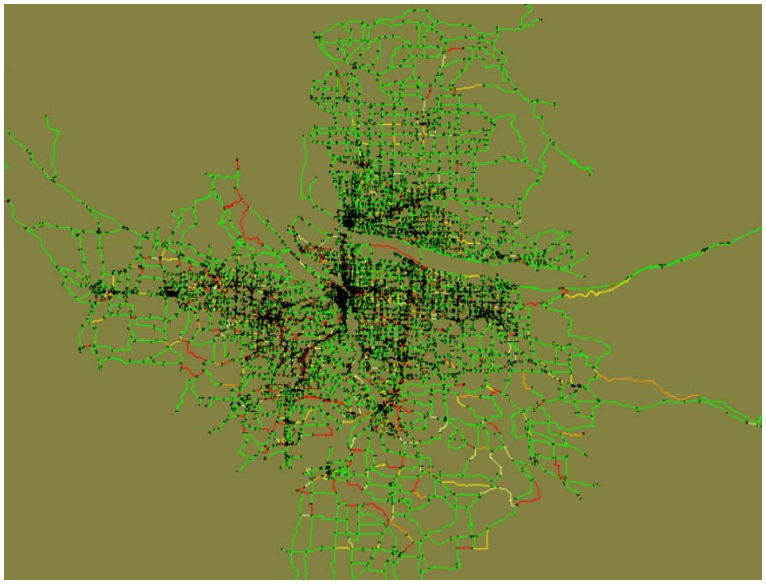


Figure 3-1 Sample DynusT Network in Portland, OR (DynusT, 2010)

The basic principles of traffic simulation vary little from one type of traffic simulation to the next. The overall procedure of developing and applying traffic simulation modeling to a traffic analysis consists of seven steps, four of which are part of the model set up. A flow chart of the model set up for traffic analysis is shown in Figure 3-2.

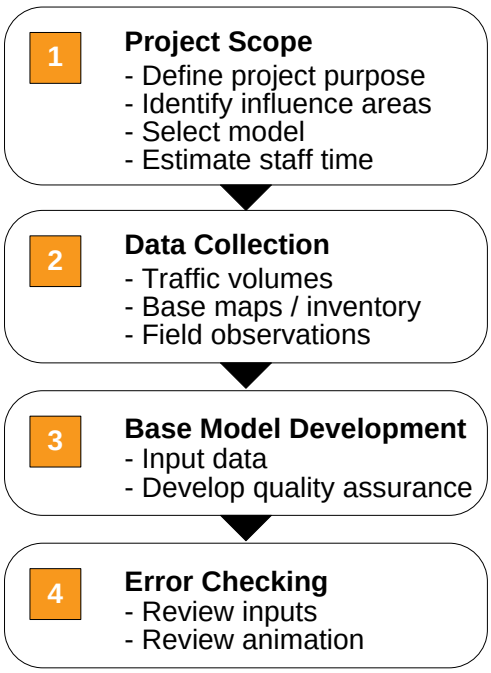


Figure 3-2 Flow Chart of Model Set Up
(Source: Modified from Traffic Analysis Toolbox Volume III - Dowling *et al*., 2004)

3.2.1.1. Project Scope

An important first step for any project is assessing its scope. When it comes to traffic modeling, thoroughly scoping out the project can be very useful in deciding what traffic analysis tool is best for the goals of the project. Projects that require modeling of large geographic areas, faster

computing times, or networks with several routes for drivers to take should consider using mesoscopic modeling; the drawback being a loss in fidelity in the output results. The microscopic simulation section further elaborates on this topic.

3.2.1.2. Data Collection

Setting up the model cannot be done until all of the necessary data are complete. All of the model setup information falls into one of three groups: Network, Control, or Movement.

Network:
The network data contain all of the links and nodes that geographically build the network. Links represent roadways and nodes and points on the map where multiple roads connect. A node could be an intersection, a freeway ramp, or simply a point where the road curves to make for a more accurate representation of the roadway network.

Control:
The control data are needed for intersections where signals or signs are used to govern vehicle movements. The data would include information on the location and timing of traffic signals or the locations of Stop or Yield signs. It also includes data for ramp metering or variable message sign (VMS) information being provided to drivers.

Movement:
The movement data are also necessary for intersection control and define how a vehicle moves when at an intersection. These data work hand-in-hand with the Control data to accurately move vehicles throughout the network.

3.2.1.3. Base Model Development

To complete this step all of the data that were collected need to be organized and formatted correctly into the proper program-specific input data so that the modeling tool will be able to read and use the data without problems. Mesoscopic traffic models can be very data intensive and require a large number of input data in order to build an entire network.

3.2.1.4. Error Checking

The primary purpose for Error Checking is to ensure that the model being developed will accurately simulate what is occurring or will occur in real networks. Data calibration and validation will be discussed in detail in the coming sections.

3.2.2. Data Preparation

To prepare a mesoscopic simulation model, data are typically needed for estimating supply and demand parameters. Data for supply parameters are speed, volume, and density from each segment type of the transportation network that is being studied. Data for demand parameters (i.e., origin destination demand matrix) are the historical origin-destination (OD) matrix and observed counts.

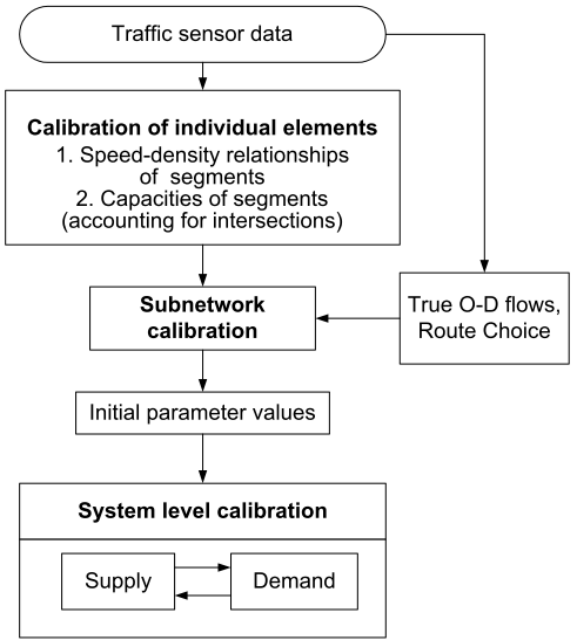
Conducting data preparation allows for quality assurance in the input data of the study. It is made up of review, error checking, and the reduction of the data collected in the field (Dowling *et al*., 2004). Data verification and validation should be performed during the data preparation step. The following are data verification and validation checks:

Data Verification and Data Validation
▪ Geometric and control data should be reviewed for apparent violations of design and/or traffic engineering practices. Sudden breaks in geometric continuity (such as a short block of a two-lane street sandwiched in between long stretches of a four-lane street) may also be worth checking with people who are knowledgeable about local conditions. Breaks in continuity and violations of design standards may be indicative of data collection errors. ▪ Internal consistency of counts should be reviewed. Upstream counts should be compared to downstream counts. Unexplained large jumps or drops in the counts should be reconciled. ▪ Floating car run results should be reviewed for realistic segment speeds. ▪ Counts of capacity and saturation flow should be compared to the HCM estimates for these values. Large differences between field measurements and the HCM warrant double checking the field measurements and the HCM computations.

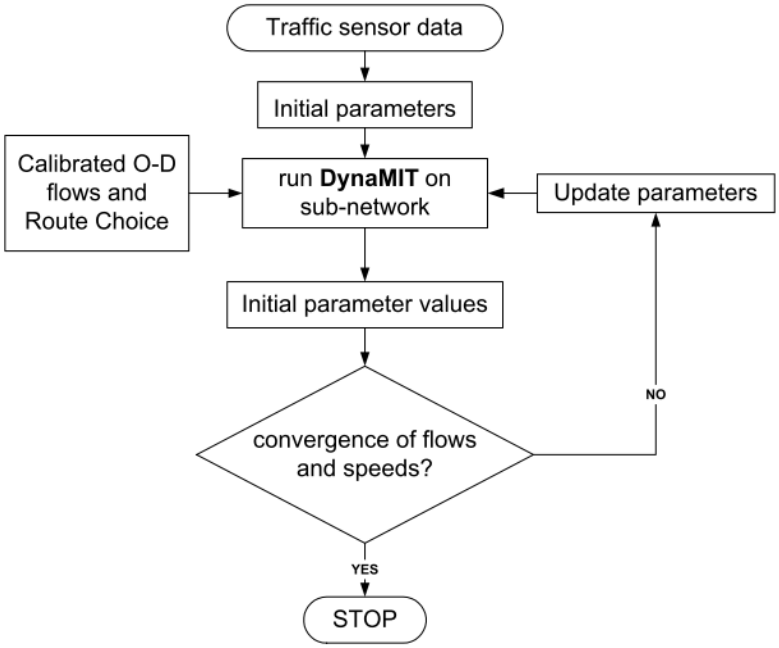
(Source: *Traffic Analysis Toolbox Volume III* - Dowling *et al*., 2004)

3.2.3. Traffic Model Calibration for Normal Conditions

Calibrating the mesoscopic traffic model is based on the same principle as calibration of any model. Real data such as vehicle counts, speed studies, and travel time data; the Highway Capacity Manual standards; and historic origin and destination demand data are all useful for calibrating and validating the model. Figure 3-3 briefly outlines the process of calibrating supply and demand data for a mesoscopic simulation. Figure 3-3(a) shows calibration as a three-step process: disaggregated level, sub-network level, and system level calibration. The disaggregated level calibration deals with calibration over entire segments of the speed-density relationships and the capacity. As shown in Figure 3-3(b), the sub-network calibration discusses more specific procedures. The sub-network calibration is the process of estimating and calibrating demand on the segment level. Finally, system-level calibration is calibrating supply and demand parameters on the network scale to ensure that the supply and demand match up with one another.



(a) Framework for supply and demand calibration



(b) Subnetwork calibration

Figure 3-3 Calibration of Both Supply and Demand Data Process Flow Chart (Kunde, 2000)

Some specific methods for calibrating both the supply and demand parameters are discussed further below.

3.2.3.1. Supply Parameters

Supply parameters are the characteristics of a roadway that describe its ability to move vehicles: capacity, speed, flow. Supply parameters are determined by some type of traffic flow model. Traffic flow models dictate how vehicles move in general. Individual vehicle movements are not simulated in mesoscopic models. Mesoscopic traffic flow models use a macroscopic traffic flow model.

The following model is the traffic flow model used by DynaMIT software to determine the supply parameters (Park *et al*., 2004). This model uses the speed and flow relationship.

$$q = q_{obs},\ u = u_f \qquad \text{if } \frac{q_{obs}}{u_{obs}} \leq k_0 \tag{3-1}$$

$$q = u_{obs}\left\{k_{jam} \cdot \left[1 - \left(\frac{u_{obs}}{u_f}\right)^{\frac{1}{\alpha}}\right]^{\frac{1}{\beta}} + k_0\right\} \qquad \text{if } \frac{q_{obs}}{u_{obs}} > k_0 \tag{3-2}$$

Where:

q_{obs} = field flow (vph)
u_{obs} = field speed (vph)
q = estimated flow (vph)
u = estimated speed (mph)
u_f = free flow speed (mph)
k_0 = free flow density (veh/mile/lane)
k_{jam} = jam density (veh/mile/lane)
α and β=parameters

This is a two-regime function, which means that free-flow conditions and non-free flow conditions are treated separately. In the free flow regime u is the free flow speed while curve fitting is done to estimate speed in the second regime. The parameters α, β are determined by plotting and examining the data collected. DYNASMART and DynusT use similar traffic flow models.

As noted, to calibrate the supply parameters for normal conditions, speed, flow, and density data from a real network during normal conditions need to be collected. The data should then be input into one of the model equations shown above. The model equation could be transformed into a linear model so that linear regression analysis can be performed and values for traffic flow model parameters can be determined (i.e., α and β in speed-flow relationship equation). This process can be repeated if necessary to improve the accuracy of the supply parameters. This process is well illustrated in the supply parameter calibration procedure.

Supply Parameter Calibration Procedure
Step 1 Process observation data Step 1.1 Categorize the traffic data (speed and occupancy), for each location. Step 1.2 Convert occupancy into density Step 1.3 For each location, perform Steps 2 through 5. Step 2 Fit the data into a dual-regime model. For initial kbp of 10 vpmpl, do the following: Step 2.1 Divide the data set into to subsets based on the initial k_{bp}, that is, the first and second regime observations. Step 2.2 For the first regime, the free-flow speed, u_f, is estimated as the mean of the speeds. Root mean squared error for speeds is also calculated. Step 2.3 For the second regime, set v_0 and k_{jam} based on the observations, that is, the minimum speed observed and maximum density observed. Step 2.4 Transform the second regime data, speed and density, as follows: $$Y = \ln(v_i - v_0), X = \ln\left(1 - \frac{k_0}{k_{jam}}\right)$$ $$\text{Let } b = \ln(v_f - v_0)$$ Step 2.5 Perform linear regression of the function $Y = \alpha X + b$ to estimate α and b. Step 2.6 Recover v_f from the estimated b, that is $v_f = e^b + v_0$ Step 2.7 Calculate R-squared value for the second regime. Step 2.8 Calculate difference in estimated speeds at the joint of two regimes by comparing u_f in the first regime and the modeled speed value at k_{bp} in the second regime. Step 3 Increase k_{bp} by 1 vpmpl and repeat Step 2.1 to 2.8 until k_{bp} becomes 30 vpmpl. Step 4 Find the optimal value of k_{bp} based on Measures of Effectiveness (MOEs) of the fitted models for each regime and joint fit observations for the entire models. Step 5 Choose the function that best fits the data set for each weather condition.

(Source: Incorporating Weather Impacts in Traffic Estimation and Prediction Systems, Mahmassani *et al*., 2009)

3.2.3.2. Demand Parameters

A 2008 study by Park *et al*., titled *Online Implementation of DynaMIT: A Prototype Traffic Estimation and Prediction Program*, clearly describes the procedures for calibrating demand parameters during normal conditions. Their procedure is summarized in Section 3.2.3. As mentioned in the data preparation section, initial origin-destination matrices could be obtained by updating historical OD matrices. The update typically implements a gravity model with observed traffic counts. Optimization can then be used to check to see that the OD matrices are convergent. These new OD matrices are then run through the simulation to replace the original OD matrices. The resulting matrices are once again optimized for convergence and run through the simulation again. This process can be repeated as many times as necessary until the resulting matrices are well calibrated and accurately reflect the real network being simulated.

3.2.4. Calibration for Weather Impacts

As discussed, understanding the impact of weather on a transportation system could greatly improve transportation management, overall mobility, and efficiency. In order to include the impacts of weather in a traffic simulation, the supply and/or demand parameters are adjusted to

better reflect either 1) what the roadway can offer for capacity or travel speed or 2) the number of travelers commuting between origins and destinations and via which routes.

3.2.4.1. Supply Parameters

Determining the supply parameters for traffic analysis during inclement weather is a two step process. First, Weather Adjustment Factors (WAFs) must be determined and then they must be calibrated.

Weather Adjustment Factors (WAFs) are used to reduce supply parameters to a level that is more appropriate for the inclement weather conditions being observed. The three weather parameters used to determine WAFs are visibility, rain intensity, and snow intensity. Visibility is measured in miles and both rain and snow intensities are measured in inches per hour. A WAF then needs to be calculated for each supply parameter in the traffic flow model for each weather condition.

For each of the parameters, a weather adjustment factor (WAF) was calculated. WAF is calculated as:

$$F_i = \beta_0 + \beta_1 \times v + \beta_2 \times r + \beta_3 \times s + \beta_4 \times v \times r + \beta_5 \times v \times s \qquad (3\text{-}3)$$

Where,

F_i = WAF for parameter i
v = visibility (miles)
r = precipitation intensity of rain
s = precipitation intensity of snow

$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ = coefficients

Under inclement weather, the supply parameters are calculated as follows:

$$F' = F_o \times F_i \qquad (3\text{-}4)$$

Where,

F' = weather adjusted parameter
Fo = normal weather parameter
F_i = weather adjustment factor

In order to calibrate the WAFs the following calculation should be done and the results should be analyzed using linear regression analysis.

$$F_i = \frac{F'}{F_o} \qquad (3\text{-}5)$$

Where,

F' = weather adjusted parameter
Fo = normal weather parameter
F_i = weather adjustment factor

3.2.4.2. Demand Parameters

The demand parameters are origins, destinations, and demand volumes. If weather causes drivers to change their destination, change the time at which they make their trip, or results in a change in the number of drivers using a particular route in order to complete their travel, then the

demand parameters for that particular weather event would be unlike the normal condition. Understanding these decisions would require understanding the behavior of every driver on the road. For the purposes of calibrating the simulation, historic driver and weather data can be paired up and calibrated to generate factors similar to the Weather Adjustment Factors used in the supply parameter calibration section.

One method for determining and calibrating demand parameters is outlined by Samba and Park (2009). This study is one of the first attempts to analyze the impact of inclement weather on demand parameters. In their study, they proposed a probabilistic approach to determine the percent average reduction of traffic demand under rainy and snowy conditions for seven sites surrounding major central business districts in Minnesota and Virginia. Factors including time-of-day and varying precipitation intensity were incorporated in the analysis. Weather data for Minnesota and Virginia were collected from the National Oceanic and Atmospheric Administration hourly precipitation report for the years 2006 and 2007. Traffic data was grouped into 1-hour intervals to be consistent with the weather data format. They separated traffic data by each month and parsed out weekends, holidays, and any other non-inclement weather days that produced atypical Average Daily Traffic (ADT) values or hourly volume curves (e.g., atypical ADT resulting from construction). Then a spreadsheet of the inclement weather days was developed in the analysis. The non-inclement weather days were studied so that the mean volume and standard deviation could be produced for a typical dry day for each month. The yielded mean was used as a baseline to compute the percent difference of inclement weather volume for each hour. Equation 3-6 presents the percent difference equation that was used in the analysis.

$$Percent\ Difference = \frac{(Inclement\ Weather\ Volume - Dry\ Baseline\ Average\ Volume)}{Dry\ Baseline\ Average\ Volume} \tag{3-6}$$

A 95 percent confidence value can be determined with the use of the yielded standard deviation. The 95 percent confidence value is used in analyses to calculate a threshold value that is above and below the mean that is expected 95 percent of the time. If the absolute percent difference of a precipitation day's hourly volume exceeds the threshold value then it can be stated with 95 percent confidence that the volume falls outside the expected range and can be attributed to the impact of inclement weather.

The percent difference can be used to predict the changes to traffic demand that are caused by inclement weather conditions. Users can follow the proposed procedure:

Traffic Volume Reduction Procedure
Step 1: Determine precipitation impact probability. Depending on the amount of rain or snow, V percent can be determined from the maximum statistically significant volume. Step 2: Determine a median percent reduction in traffic demand at a given hour PM-HR. The median percent reduction can be obtained using Equation 3-2. Step 3: Determine traffic volume reduction as: Step 1.1 Categorize the traffic data (speed and occupancy), for each location. Volume Reduction (Δ) = V percent × PM-HR Where, V percent = Probability of significant volume reduction, and PM-HR = the median percent reduction from the mean at a specific hour

(Source: Samba and Park, 2009)

This procedure can be best explained with an example:

Volume Reduction Example Problem
Step 1: For light snow event, the "V percent" value is 76 percent. Step 2: From using Equation 3-2, the median percent of volume reduction due to snow event between 4 pm and 5 pm is 32 percent. Step 3: A traffic volume reduction of 24.3 percent as obtained from 76 percent × 32 percent. A traffic engineer can use multiple simulation runs to consider day-to-day variability in traffic demands. Let's assume a total 50 replications will be made. As seen above, Step 1 determined V percent of 76 percent. Thus, traffic volume will significantly change with a 76 percent probability. Consequently, 38 cases out of 50 total runs will have reduced traffic demand volumes. Furthermore, Step 2 shows 32 percent reduction in traffic demand. Thus, the 38 cases will be evaluated with the 32 percent reduced traffic demand, while the remaining 12 runs will be made with the original traffic demand. Inclement weather impact can be estimated from these 50 runs using a distribution of selected measures of effectiveness (e.g., average speed or average travel time).

(Source: Samba and Park, 2009)

3.2.5. Performance Measures

To ensure that the model is working properly and providing reliable results, it needs to be validated against real data from the network being modeled. This is done by comparing the mesoscopic model outputs and field measurements. The following parameters can be established as performance measures for mesoscopic traffic analyses:

- Travel Time;
- Speed;
- Delay;
- Queue;
- Stops; and
- Density.

It is important that a performance measure be appropriate (i.e., it can provide an adequate representation of at least one objective established in the analysis) and measurable.

3.2.6. Weather Model Implementation and Analysis

This section presents mesoscopic model implementation and analysis under inclement weather conditions.

3.2.6.1. Supply Parameters Calibration

The two methods for determining and calibrating supply parameters are (1) obtaining inclement weather data and analyzing it by fitting it to the traffic flow models or (2) applying Weather Adjustment Factors (WAFs).

The direct curve fitting method estimates parameters of a traffic flow model directly using flow and speed data observed during inclement weather conditions. Figure 3-4 shows the steps for this process. First the data needs to be sorted by weather condition. A speed-flow curve can be plotted and the traffic flow model parameters can be determined. It is noted that K_{jam} represents jam density and alpha and beta are calibration parameters of the mesoscopic traffic model.

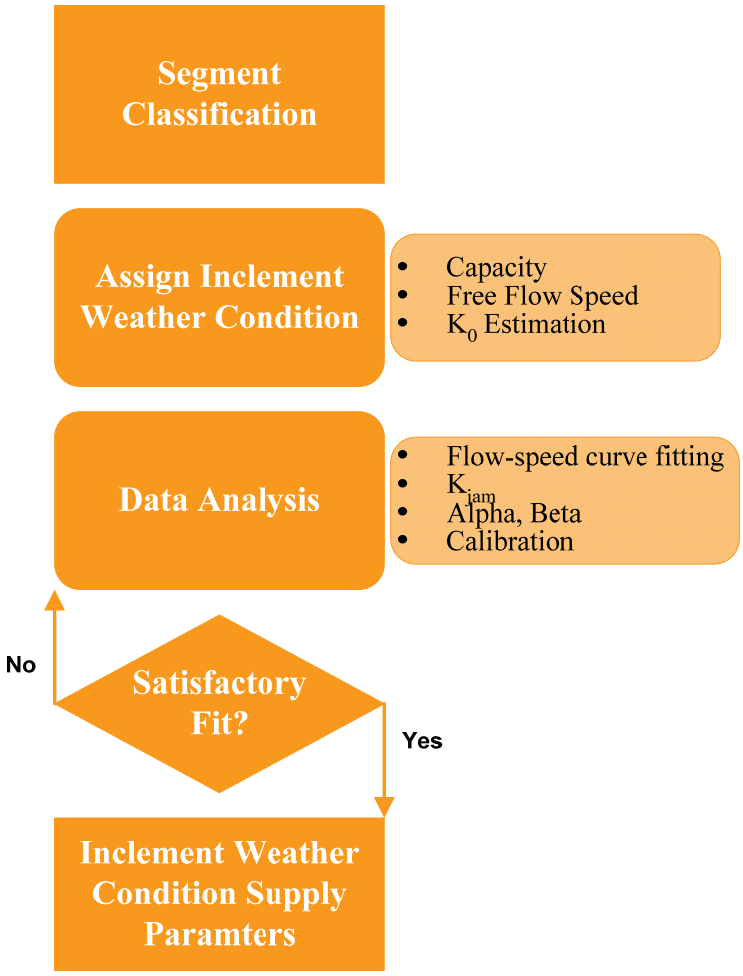


Figure 3-4 Supply Parameter Calibration Procedure
(Source: Modified from *Field Evaluation of DynaMIT in Hampton Roads*. Park *et al*., 2004)

Table 3-1 shows the supply parameters for inclement weather conditions that were estimated for the DynaMIT program using Hampton Roads data by following the supply parameter calibration procedure shown in Figure 3-4.

Table 3-1 Calibrated Supply Parameters

Segment Type	v_f (mph)	k_{jam} (vplvm)	α	β	Capacity (vphpl)	k_0 (v/lm)
1 lane basic freeway	61	160	5.21	1.68	2000	15
3 and 3+ lane basic freeway	66	160	5.33	1.65	2100	15
2 lane merging area	61	160	4.91	1.68	2150	15
3 and 3+ lane merging area	64	160	5.16	1.71	2100	15
2 lane diverging area	59	160	11.17	2.20	2000	15
3 and 3+ lane diverging area (I-64 and I-564)	61	160	11.18	2.23	2100	15
3 and 3+ lane diverging area (I-264)	56	160	5.16	1.85	2100	15
Weaving area (I-64 and I-564)	61	160	9.62	2.05	2000	15
Weaving area (I-264)	56	160	8.52	2.07	1900	15
Ramps	46	150	1.82	1.52	1900	10

The WAF method can be used to calibrate the supply parameter for inclement weather conditions. The method is already discussed under Section 3.2.4. The WAF method is a regression model capturing impacts of different weather conditions (e.g., normal, light rain, moderate rain, and light snow). The regression model is developed on the basis of speed and density relationship functions estimated for various weather conditions. Table 3-2 presents calibrated coefficients of the weather adjustment factors.

Table 3-2 Weather Adjustment Factor Coefficients

Input Data	Traffic Properties	β0	β1	β2	β3	β4	β5
Traffic Flow Model	1. Speed-intercept, (mph)	0.91	0.009	-0.404	-1.455	0	0
	2. Minimal speed, (mph)	1	0	0	0	0	0
	3. Density break point, (pcpmpl)	0.83	0.017	-0.555	-3.785	0	0
	4. Jam density, (pcpmpl)	1	0	0	0	0	0
	5. Shape term alpha	1	0	0	0	0	0
Link	6. Maximum service flow rate, (pcphpl or vphpl)	0.85	0.015	-0.505	-3.932	0	0
	7. Saturation flow rate, (vphpl)	0.91	0.009	-0.404	-1.455	0	0
	8. Posted speed limit adjustment margin, (mph)	0.91	0.009	-0.404	-1.455	0	0
Left-Turn Capacity	9. g/c ratio	0.91	0.009	-0.404	-1.455	0	0
2-way Stop Sign Capacity	10. Saturation flow rate for left-turn vehicles	0.91	0.009	-0.404	-1.455	0	0
	11. Saturation flow rate for through vehicles	0.91	0.009	-0.404	-1.455	0	0
	12. Saturation flow rate for right-turn vehicles	0.91	0.009	-0.404	-1.455	0	0
4-way Stop Sign Capacity	13. Discharge rate for left-turn vehicles	0.91	0.009	-0.404	-1.455	0	0
	14. Discharge rate for through vehicles	0.91	0.009	-0.404	-1.455	0	0
	15. Discharge rate for right-turn vehicles	0.91	0.009	-0.404	-1.455	0	0
Yield Sign Capacity	16. Saturation flow rate for left-turn vehicles	0.91	0.009	-0.404	-1.455	0	0
	17. Saturation flow rate for through vehicles	0.91	0.009	-0.404	-1.455	0	0
	18. Saturation flow rate for right-turn vehicles	0.91	0.009	-0.404	-1.455	0	0

(Source: *Incorporating Adverse Weather Impacts in Dynamic Traffic Simulation-Assignment Models: Methodology and Application*, Dong *et al*., 2010)

The results of implementing weather adjustment factor were illustrated by Dong *et al*. (2010) when they simulated a stretch the of I-95 corridor and nearby arterial networks in Maryland from Washington D.C. to Baltimore. The three scenarios simulated were a clear and normal weather day, a moderate rain event, and a heavy rain event. Moderate rain is defined as visibility of 1 mile and rain intensity of 0.2 inch/hour, while heavy rain is defined as visibility of 0.5 miles and rain intensity of 0.5 inch/hour. Supply parameters for these weather conditions were adjusted using WAFs from Table 3-3. As shown in Figure 3-5, the time-varying network travel times became longer as weather conditions became worse. This is due to rain impacts on reduced capacity and saturation flow rates.

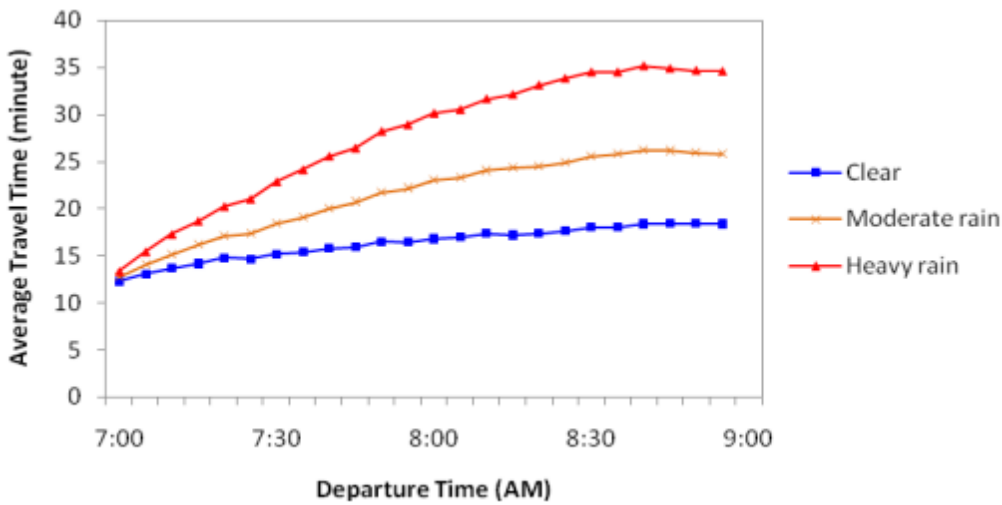


Figure 3-5 Travel Time Comparisons under Three Weather Conditions
(Source: *Incorporating Adverse Weather Impacts in Dynamic Traffic Simulation-Assignment Models: Methodology and Application*, Dong *et al*., 2010)

3.2.6.2. Demand Calibration

The estimation of demand parameters can be approached two ways: (1) by adjusting demand "on-the-fly" or (2) by developing a mathematical representation of how demand may change.

The first method calibrates demand (i.e., OD matrix) by reactively updating OD demand based on real-time sensor counts during inclement weather conditions. This makes sense because studies have shown few changes during morning peak hours but some reductions during non-peak hours under inclement weather conditions. An example of the real-time operation of the DynaMIT program's application is in the Hampton Roads area of Virginia (Park *et al*., 2004). While the real-time implementation was not conducted during inclement weather conditions, dynamic OD estimation was implemented based on real-time sensor counts. Thus, demand (i.e., the OD matrix) was updated using observed traffic counts to reflect changes in network travel behaviors, including weather, recurrent, and non-recurrent events.

The second method is less clear because there is no one model available that perfectly describes the factors that determine whether or not a person will decide to make a trip during various weather conditions. It is not clear what impact weather has on the driver's decision to make a trip. This method uses probabilistic demand adjustment factor based on empirical data observed during inclement weather conditions. The method is already described earlier in Section 3.2.4.2 Samba and Park (2009) applied this method using traffic and weather data from several locations in Virginia and Minnesota. The resulting probabilities of significant volume change under inclement weather as well as averages and ranges of volume changes are shown in Table 3-3. Note that the probability of significant volume change is determined when volume reduction is bigger than normal traffic volume variations at a given location.

Table 3-3 Demand Adjustment due to Inclement Weather Conditions

Weather Condition	Probability of Weather Impacted Volumes	Volume Reduction Change	Average Volume Reduction
Light Rain	16.6%	1.0% to 6.3%	2.32%
Heavy Rain	31.3%	3.1% to 4.4%	3.75%
Light Snow	76.0%	10.6% to 56.2%	28.80%
Heavy Snow	42.9%	4.7% to 30.4%	13.30%

(Source: Probabilistic Modeling of Inclement Weather Impacts on Traffic Volume, Samba and Park, 2009)

It should be noted that these estimated demand adjustment values may not be suitable for traffic operators conducting their own analyses because these values correlate to a specific study area (i.e., using these demand adjustment values will not adequately reflect the change in demand due to inclement weather). Traffic operators could follow the procedure presented in Section 3.2.4.2 to obtain their own inclement weather-based regionalized demand adjustment values.

3.2.6.3. Implementation and Analysis

A mesoscopic model under inclement weather conditions has not been implemented in the real world. Instead, a simulation study was implemented to demonstrate the impact of weather and control strategies (Mahmassani *et al*., 2009).

In the study, the calibrated supply parameters were input to the I-95 corridor and adjacent arterial networks. The supply parameters were further adjusted for inclement weather conditions including a rain event and a rain plus VMS event. Thus, three scenarios, including normal condition, are (1) a clear and normal day, (2) a rain event, and (3) rain plus VMS event. The third event includes driver information to help change the route.

In the implementation, Dong *et al*. (2010) assumed the following weather event, in Figure 3-6, during the morning peak hours.

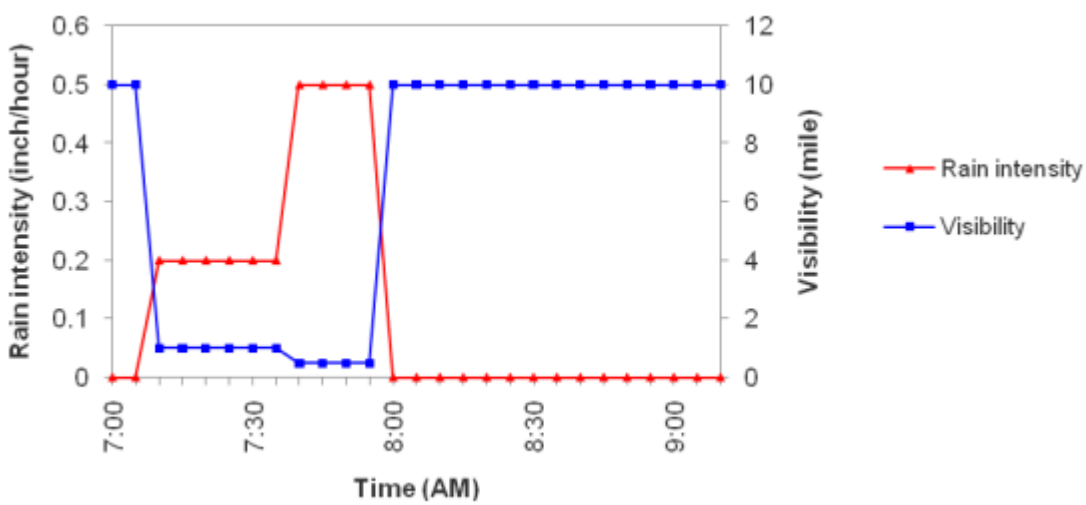


Figure 3-6 Weather Events during Peak Hour
(Source: *Incorporating Adverse Weather Impacts in Dynamic Traffic Simulation-Assignment Models: Methodology and Application*, Dong *et al*., 2010)

The results of these three simulations are seen in Figure 3-7. It is very clear that the rain scenario had the worst performance, as indicated by the low travel speeds. The rain with VMS case did not perform as well as the clear day base case, but did come close to the same speed at some points in the simulation.

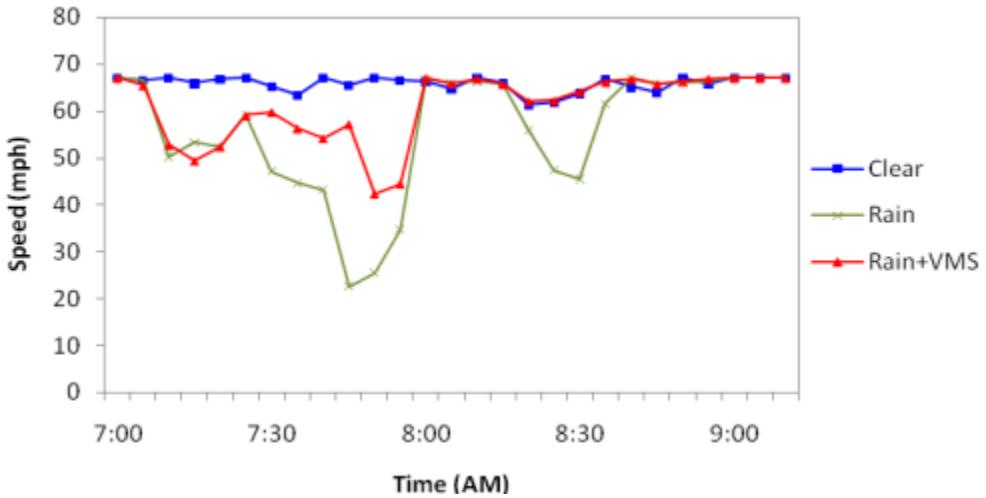


Figure 3-7 Link Speed Comparisons
(Source: *Incorporating Adverse Weather Impacts in Dynamic Traffic Simulation-Assignment Models: Methodology and Application*, Dong *et al*., 2010)

Similar studies could be performed for other weather responsive transportation management strategies that were listed previously to determine what impacts those measures have on traffic flow. Additionally, because every weather event and every roadway is unique, these simulations could be run during an event to help determine what actions should be taken at that time for that specific event.

3.3. Microscopic Analysis

Of the three types of analysis discussed in this module, microscopic analysis, based on individual vehicle movement, is the finest representation of the transportation system. Microscopic simulation models simulate the movement of individual vehicles, which can be done by using car-following models, lane-changing models, and gap acceptance models. Utilizing microscopic simulation, users can input detailed traffic data into the analysis, thereby creating an opportunity to incorporate diversity in vehicles and driver characteristics, enabling accurate simulation of real-world traffic.

3.3.1. Microscopic Traffic Simulation Model Set Up

The overall procedure of developing and applying microscopic traffic simulation modeling to a traffic analysis consists of seven steps, four of which are part of the model set up. FHWA constructed a flow chart of the model set up for microscopic analysis, which is depicted in Figure 3-1 in Section 3.2.1.

3.3.1.1. Project Scope

The project scope consists of five tasks: 1) Define project purpose, 2) Identify influence areas, 3) Select approach, 4) Select model, and 5) Estimate staff time (Holm *et al*., 2007). It is appropriate to present questions in this section that would help identify the study breadth – influence areas. Questions that can be asked pertaining to inclement weather are:

- How large is the study area that is being analyzed for inclement weather impacts?
- What weather-related resources are available to the analyst?
- What measure of effectiveness (MOEs) will be required to analyze the inclement weather impacts?

The criteria used for selecting the analytical tool are tied to the analytical approach. FHWA states that key criteria for choosing a modeling tool include technical capabilities, input/output interfaces, user training/support, and ongoing software enhancements (Dowling *et al*., 2004). To gain accuracy in simulating driver behavior during inclement weather conditions, it is necessary to choose a microscopic modeling tool such as CORSIM, VISSIM, PARAMICS, INTEGRATION and AIMSUN2.

The final task within the project scope is establishing the staff time for the project. Performing this function provides certainty that the project can be completed with the chosen approach in the allotted time. Creating a schedule for key project milestones is one approach to accomplishing this task.

3.3.1.2. Data Collection

Required input data for microscopic simulations vary based on the analytical tool and modeling application. In most microscopic modeling applications, required input data include the following:

- Road geometry (lanes, lengths, curvature);
- Traffic controls (signs, signal timing);
- Demands (entry volumes, turning volumes, O-D table); and
- Calibration data (traffic counts and performance data such as speed, queues).

For many transportation microscopic analyses, detailed data on vehicle and driver characteristics (e.g., vehicle length and driver aggressiveness) also need to be included in modeling applications. Since field data of such caliber are difficult to collect, they are established as default values in most microscopic traffic analytical tools.

When possible, data collection should be managed in such a manner that there is consistency in the datasets (Road and Traffic Authority, 2009). For instance, travel time and queue length should be recorded at the same time period as traffic count data.

3.3.1.3. Base Model Development

Once the required data is collected, one can proceed to develop a microscopic simulation model. A successful model entails the development of a model blueprint (the link-node diagram). The link-node diagram is a visual representation of the study area in terms of links and nodes. It can be created within the microscopic simulation tool or it can be created by other tools such as CAD programs. Once the blueprint is established, the model can be built in the following sequence: coding links and nodes, establishing link geometries, adding traffic control data at appropriate

nodes, coding travel demand data, adding driver behavior data, and selecting control parameters that will be used to run the model (Dowling *et al*., 2004).

3.3.1.4. Error Checking

Before any model runs are made it is both essential and beneficial to perform error checking so that the calibration process does not output distorted results. Calibrating model parameters relies on the assurance that major errors in demand and network coding are found and removed before proceeding in the model set up (Dowling *et al.*, 2004). Error checking is carried out in three primary stages: 1) software error checking, 2) input coding error checking, and 3) animation review to find obscure input errors (Holm *et al*., 2007).

3.3.2. Data Preparation

Conducting data preparation allows for quality assurance in the input data of the study. It is made up of review, error checking, and the reduction of the data collected in the field. The main purpose is to check for any discrepancies in the data (e.g., breaks in geometric continuity, unexplained large gains or losses in traffic volume, and unrealistic speeds for roadway segments) before proceeding with the analysis. Failure to do so can result in false outputs generated in the model. Please refer to FHWA's *Traffic Analysis Toolbox Volume III* for detailed data verification and validation checks.

3.3.3. Traffic Model Calibration for Normal Conditions

Traffic model calibration is the process of fine-tuning the data inputs that represent characteristics of the vehicle and driver. This is executed by comparing and adjusting absolute measures (clear, definitive, and measurable parameters) such as flow rate and mean speed. Figure 3-8 presents a flow chart of the overall calibration and validation process for microscopic traffic simulation modeling.

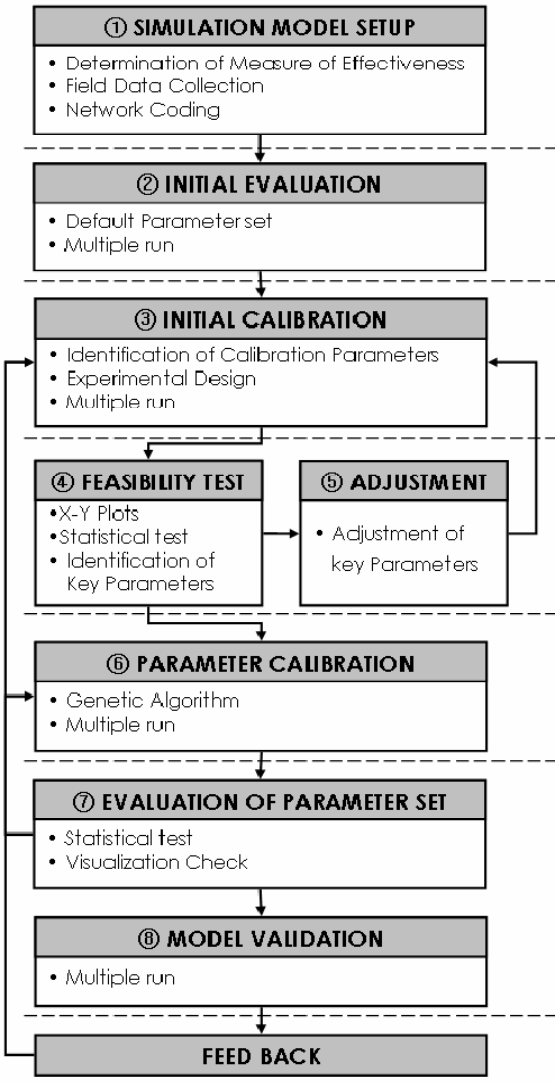


Figure 3-8 Calibration and Validation Process Flow Chart
(Source: Park and Won, 2006)

3.3.3.1. Simulation Model Set Up

The first part of the calibration and validation process involves the set up of the simulation model. It involves tasks identical to those in the microscopic traffic simulation set up previously discussed. Please refer to that section for the model set up procedure.

3.3.3.2. Initial Evaluation

The default parameter set (i.e., uncalibrated parameters) is the focus of this stage of the calibration process. A feasibility test is required at this stage. This is a test that is conducted to ensure that the field data is well represented by the distribution of the simulation results. If the default parameter set produces acceptable results (results that accurately reproduce field conditions), the calibration and validation procedure may be skipped and further analysis can be conducted with the default parameter set.

Two steps are involved in the feasibility test. First, the user needs to perform multiple runs of the simulation model using the default parameter set. Then consecutive comparisons to calibration data should be made. Figure 3-9 presents the initial evaluation process.

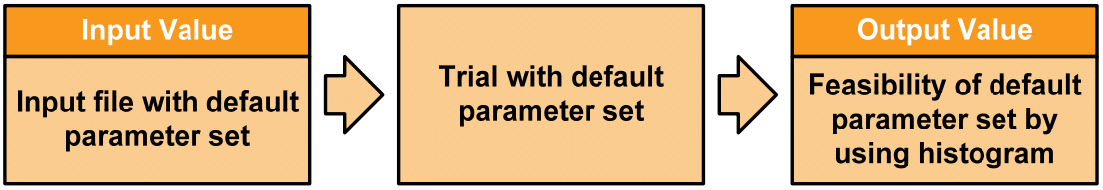


Figure 3-9 Initial Evaluation Process
(Source: Park and Won, 2006)

Multiple runs should be performed because simulation does not output the exact same results for each run. The randomly generated seed number is the cause of simulation resulting in similar but not exact outputs. It is important to include the randomly generated seed number in microscopic simulation models because its purpose is to be the decision-maker. It decides the speeds that vehicles are traveling at, the type of vehicles that are included in the simulation, and the paths that the vehicles will take. Without the randomly generated seed number, the simulation loses the stochastic nature of real world conditions.

Conducting multiple runs is a must, but how many runs should there be? Too many runs are not necessarily bad, but too many runs means time lost in performing additional simulation runs. Too few runs raise questions as to whether field conditions are well represented in the simulation runs that have been conducted. The user can perform the following procedure to estimate the minimum number of simulation runs:

1. Execute a few simulation repetitions;
2. Estimate the sample standard deviation;
3. Select an appropriate confidence level; and
4. Calculate minimum number of simulation runs.

Typically, the user should perform four simulation runs in the first step of the procedure and then analyze the calibration data from these runs. This is done so that the user can get a feel for what the distribution of simulation results will be and can make an educated guess as to how many simulation runs are required for the analysis.

The user can estimate the sample standard deviation using the calibration data from Step 1 and the following equation:

$$S^2 = \frac{\sum(x - \bar{x})^2}{N - 1} \tag{3-7}$$

Where,

x = output value for each simulation repetition
$\bar{x}$ = average value of all simulation repetitions
N = number of simulation repetitions
S = standard deviation

One can get a sense of the difference between a set of data and the average value by calculating the sample standard deviation.

Typically, a 95 percent confidence level is used in model simulation. Performing this task allows the user to decide the accuracy of results. What can be said about a 95 percent confidence level is that the user is 95 percent confident that field conditions are within the range set by the simulation outcomes for each repetition.

In finding the minimum number of simulation repetitions, the user can use Table 3-4, which consists of confidence levels ranging from 90 percent to 99 percent and the minimum number of repetitions corresponding to those confidence levels.

Table 3-4 Minimum Number of Simulation Repetitions

$C_{1-\alpha}/S$	Selected Confidence Level	Minimum Number of Repetitions
0.5	99%	130
	95%	83
	90%	64
1.0	99%	36
	95%	23
	90%	18
1.5	99%	18
	95%	12
	90%	9
2.0	99%	12
	95%	8
	90%	6

(Source: Park and Won, 2006)

To use Table 3-4, a user must calculate the ratio of confidence level to standard deviation, $C_{1-\alpha}/S$. α is the selected confidence level and $C = 1 - \alpha$. If the confidence level is 95 percent then C equals 0.05.

So a user now has an estimated the minimum number of simulation runs that are required in the analysis and has conducted them. Now, the user has to determine the validity of the default parameter set. This can be done with a histogram or X-Y plot. Both are visual aids to the user to determine the worth of the default parameter set.

The histogram shows the frequency of data points and presents the modeler to view the distribution of simulation output data. For a feasible default parameter set, the field data must fall within the distribution set by the simulation output data.

Unlike a histogram, the frequency of a particular value is not required to create an X-Y plot. The level or location of each simulation output data is what is required. On an X-Y plot, each data point shows the location of where two variables, in this case two performance measures, intersect. An example showing how a user can determine the feasibility of the default parameter set may be helpful here. Let's assume that the field-collected data for performance measures 1 and 2 range from 62 to 86 and 8.3 to 15.2, which is outlined in the dark-shaded box seen in Figure 3-10.

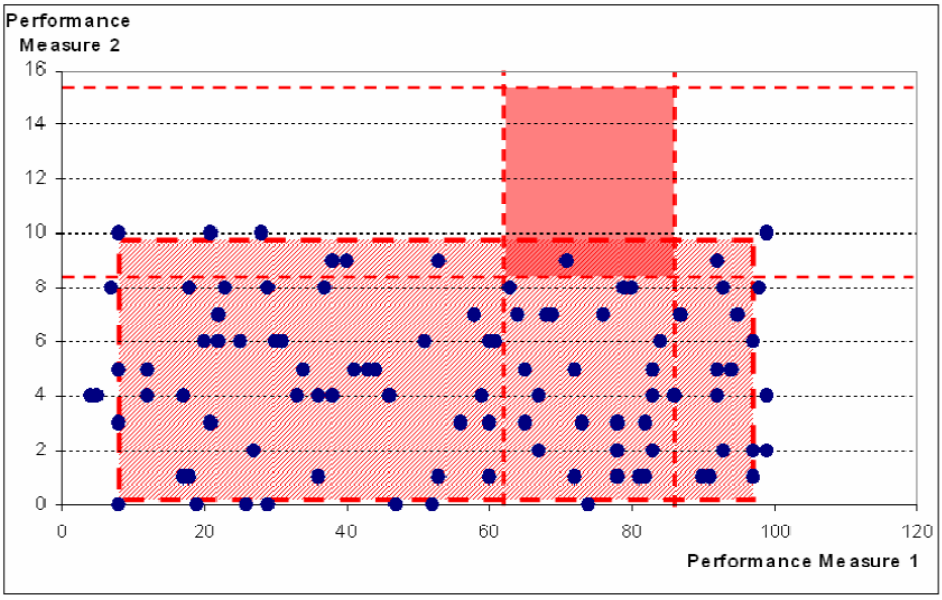


Figure 3-10 Example of X-Y plot with Acceptable Results
(Source: Park and Won, 2006)

From Figure 3-10, the light-shaded box represents the 90 percent confidence interval region of simulation output data. If the two boxes overlap one another, then it can be concluded that the default parameter set is feasible. However, if they do not overlap then the default parameter set is unfeasible.

3.3.3.3. Initial Calibration

Initial calibration consists of three steps: 1) identifying calibration parameters, 2) sampling different cases within a determined range, and 3) verifying whether the determined ranges are appropriate. Calibration parameters vary depending on the modeling applications.

The calibration parameters are values that the user places in the simulation model so that the simulation conditions accurately represent field conditions. The calibration parameters vary based on the simulation model. In CORSIM, calibration parameters range from mean value of lost start-up time to minimum deceleration for lane change to desired free flow speed.

Once the calibration parameters are identified, a user should begin sampling from the combinations of a parameter set. The combinations of the parameters can be quite large, to the point where they exceed millions. If this is the case, then it would be unpractical to sample these combinations because such a process would last years. To avoid this obstacle, a user can use an algorithm called Latin Hypercube Design (LHD) which reduces the number of combinations that need to be analyzed while still maximizing the parameter cover.

Like the previous step of determining the feasibility of the default parameter set, a user needs to conduct multiple runs using the selected parameter sets. Doing so will allow the user to simulate the stochastic nature of field conditions. After conducting multiple runs, the user needs to determine if the parameter sets provide acceptable ranges. Procedures used to validate the default parameter set can be used here. Whichever procedure is used, histogram or X-Y plot, the field conditions must fall within the 90 percent confidence level in order for the parameter set range to be considered acceptable.

3.3.3.4. Feasibility Test and Adjustment

If the parameter set range from the initial calibration was determined unacceptable (field measures did not fall within the 90 percent distribution of the range), then conducting a feasibility test is necessary in order to find an appropriate parameter set range to use in the main calibration process. This can be conducted by two methods: X-Y plots or a statistical method known as Analysis of Variance (ANOVA). These two methods allow the user to identify the key calibration parameters. When using the X-Y plots, the user should look for a relationship that exists between the calibration parameter and the measure that goes along with it. If the data points on the plot show a relationship, then that X-Y plot is one of a key parameter. If the data points are scattered and a relationship cannot be made, then the calibration parameter is not be considered a key parameter. Like the X-Y plots, the user should look for a relationship among the calibration parameter and the corresponding measure when using ANOVA. This method provides statistical outputs such as Sums of Squares, F-statistic, and P-value. For the purposes of identifying key parameters, the p-value is the most important statistic in ANOVA. If the p-value of a parameter is less than the confidence interval, then that parameter is a key calibration parameter.

Once the key parameters are identified, the user can adjust the calibration parameter ranges so that they reflect field conditions. This can be done by merely shifting the parameter range of the X-Y plot used for the key parameter identification step. Remember to shift the parameter range so that data from the field is well represented. A feasibility test needs to be conducted again once the parameter ranges are adjusted.

3.3.3.5. Parameter Calibration

Once an acceptable parameter range is determined, the next step is to select a parameter set that best represents data collected from the field. An optimization method, such as the Genetic Algorithm (GA), is used to complete this task. The GA uses a specific number of digits, known as the chromosome. These digits, which are generated at random, correspond to calibration parameter values. When the digits are generated, the parameter values are generated as well. A randomized simulation run can be completed afterwards.

3.3.3.6. Evaluation of Parameter Set

For this step, the user should make an assessment of the performance of the calibrated parameter when it is set to another parameter set. This allows the user to confirm that the calibrated parameter will output more accurate results than the other parameter set. Comparing the default parameter set to the calibrated parameter set could be completed in the evaluation step. As conducted in previous steps, the user should conduct multiples runs for each model using a different parameter set and check the feasibility for each model using a histogram.

3.3.3.7. Model Validation

Validation of the untried data is the last step of the model calibration and validation procedure. It is imperative to conduct this step because, if successful, it will show that the calibrated parameter set is versatile. In the validation process, the model needs to be tested with the untried data. Multiple runs are conducted with the random seeded numbers and the calibrated parameter set. The user needs to create a histogram of the simulation output data so that there is a visual representation of it. The field data must fall within the 90 percent confidence interval region (acceptable region) in order to validate the fine-tune process of calibration applied to the parameter set. Figure 3-11 shows the histogram format used for model validation.

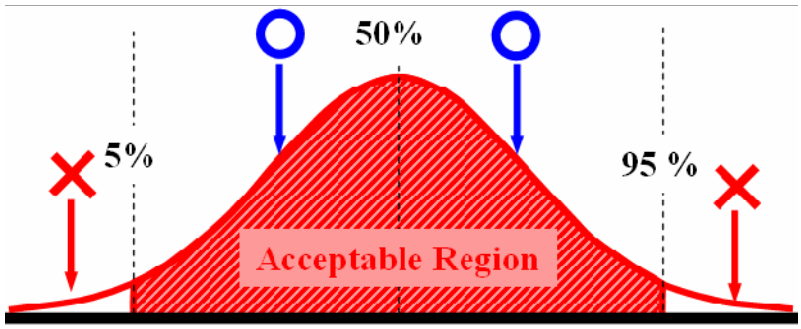


Figure 3-11 Concept of Acceptable Region
(Source: Park and Won, 2006)

For additional information on the calibration and validation procedure, please refer to *Microscopic Simulation Model Calibration and Validation Handbook* (Park and Won, 2006) and Traffic Analysis Toolbox Volume IV: Guidelines for Applying CORSIM Microsimulation Modeling Software (Holm *et al*., 2007).

3.3.4. Calibration for Weather Impacts

Calibration for weather impacts is no easy feat but it is possible to do in microscopic traffic simulation modeling. This section discusses the methods that others have used to calibrate supply and demand parameters for inclement weather in existing microscopic traffic simulation models.

3.3.4.1. Supply Parameters

Supply parameters are defined as the conditions that the roadway can offer to drivers such as roadway capacity. This parameter has been the focus of several past and recent studies on the effect of inclement weather on the transportation system.

Based on the study conducted by FHWA (2009), it was recommended that longitudinal models (i.e., car-following, deceleration, and acceleration models) and other models be used to reflect field conditions during inclement weather. To calibrate for weather impacts in microscopic traffic analyses, weather conditions are used as the basis for the adjustment of macroscopic traffic stream parameters. These weather conditions are represented by Weather Adjustment Factors (WAFs). The macroscopic traffic stream parameters that are adjusted by these WAFs include the following: free-flow speed (uf), speed at capacity (uc), and saturation flow at capacity (qc). Weather Adjustment Factors are a function of precipitation type, intensity level, and visibility level as seen in Equation 3-8:

$$WAF = \alpha_1 + \alpha_2 \cdot i + \alpha_3 \cdot i^2 + \alpha_4 \cdot v + \alpha_5 \cdot v^2 + \alpha_6 \cdot iv \qquad (3\text{-}8)$$

Where,

i = Precipitation intensity (cm/h)
v = Visibility level (km)
iv = Interaction between precipitation and visibility
α_1, α_2, α_3, α_4, α_5, α_6 = Calibrated model parameters

A user can determine the microscopic traffic simulation parameters after estimating the macroscopic traffic stream parameters that were adjusted using WAFs.

The calibration of traffic stream of longitudinal motion can be accomplished in the microscopic simulation analysis through steady-state modeling and nonsteady-state modeling. Steady-state

(stationary) conditions occur when the traffic remains relatively constant over a short period of time and distance. For nonsteady-state behavior, analysis involves the movement of vehicles from one state to another. When calibrating for nonsteady-state behavior, the user can simulate capacity reduction, which is a result of traffic conditions such as congestion and capacity loss during lost start-up time. Calibration of steady-state and nonsteady-state behaviors can be performed with the use of car-following models.

Car-following models explain the behavior of drivers in vehicles that follow the lead vehicle. Currently, several car-following models exist in various microsimulation software packages. These include:

- The Pitt model (CORSIM);
- The Wiedemann74 and 99 models (VISSIM);
- The Gipps' model (AIMSUN2);
- The Fritzsche's model (PARAMICS); and
- The Van Aerde model (INTEGRATION).

One can calibrate car-following models with the use of the adjusted macroscopic traffic stream parameters: free-flow speed (u_f), speed at capacity (u_c), saturation flow at capacity (q_c), and jam density (k_j). Remember, these macroscopic traffic stream parameters are influenced by inclement weather. So using these parameters will allow users to calibrate the car-following models under inclement weather conditions.

The calibration procedure for steady-state behavior in these car-following models is as follows (Hranac *et al*., 2006):

1. Define the functional form to be calibrated;
2. Identify the dependent and the independent variables;
3. Define the optimum set of parameters; and
4. Develop an optimization technique to compute the set of parameter values.

Additional methods of calibrating for weather impacts exist. These methods include: deceleration modeling, acceleration modeling, gap acceptance modeling, and lane-changing modeling. For more information on the feasibility of incorporating weather-related factors into these analyses, please refer to the FHWA report (2009) *Microscopic Analysis of Traffic Flow in Inclement Weather* at: http://ntl.bts.gov/lib/32000/32500/32539/tfiw_final.pdf.

3.3.4.2. Demand Parameters

Very few studies have been successful in modeling the impacts of inclement weather on demand (e.g., traffic volume) because of the random nature of driver behavior. Studies that analyzed the impact of inclement weather on traffic conditions typically assumed that demand remains at volumes observed under normal, dry conditions. This approach quantifies the effect of inclement weather, but the accuracy of traffic demand behavior suffers.

A probabilistic approach, as discussed in Section 3.2.4.2, can be used to determine the percent of average reduction in traffic demand under inclement weather, such as rainy and snowy conditions. Please refer to Section 3.2.4.2 to obtain the procedure that was used to calibrate demand parameters for inclement weather.

3.3.4.3. Driver Behavior Parameters

Driver behaviors influence the supply and demand parameters. For instance, a driver who decides not to travel affects traffic demand, and a driver who slows during inclement weather conditions will have lower speed, longer saturation headway, and lost startup time. Saturation headway and lost startup time are considered driver behavior parameters because they are developed in response to supply and demand traffic parameters. Calibrating for these two parameters can be accomplished, but the procedure will differ based on the analysis. Users can obtain such driver behavior parameters (e.g., saturation headway and/or lost startup time) from the field during inclement weather conditions.

3.3.5. Performance Measures

The purpose of conducting simulation models is to recreate field conditions and to evaluate the impacts of untried strategies over the base case. In order to adequately assess the performance of a transportation facility, a user should select performance measures for their analyses. These measures give insight into the performance of a project's traffic operations objectives. The performances measures used in mesoscopic traffic analyses (see Section 3.2.5) can also be used in microscopic traffic analyses. Such performance measures include travel time, speed, delay, queue, stops, and density. The user may also establish a reliability measure (e.g., travel time variance) as a performance measure for microscopic traffic analyses. Travel time variance would be easier to obtain for microscopic traffic analysis rather than mesoscopic analysis because microscopic traffic analysis has the capability to model individual movement of vehicles.

When choosing performance measures they should, of course, be measureable, and have some relation to the objective of the project.

3.3.6. Model Implementation and Analysis

Performing model implementation involves model development. This includes: model setup, data preparation, and calibration and validation. Please refer back to the procedure for simulation model setup discussed in Section 3.3.1.

Because the focus of this discussion is on weather model implementation, it is imperative to discuss the procedures that others have adopted to incorporate the effects of inclement weather in their analyses. Since a universally "correct" method of modeling to determine inclement weather impacts is nonexistent, procedures will vary.

3.3.6.1. Data Preparation

Modeling the impact of inclement weather in traffic analyses is a complex task. Therefore, users should reduce data to prevent increasing the complexity of the analysis. This can be accomplished by simply setting limitations on what will be analyzed, such as restricting the number of lanes or datasets in the analysis. Use the objectives and goals of the analysis to decide which values are important and should remain in the analysis

3.3.6.2. Calibration

To calibrate for weather impacts, a user can use macroscopic traffic stream parameters that have been adjusted to reflect inclement weather conditions in microscopic simulation modeling. Weather Adjustment Factors (WAFs) can be used to adjust the key macroscopic traffic stream parameters: free-flow speed, speed at capacity, and saturation flow at capacity. Please refer to Section 3.3.4 for more information on the calibration for weather impacts.

3.3.6.3. Model Implementation of Weather Impacts

Studies that have attempted to model the impact of inclement weather on the transportation system do not all use the same approach or method for model implementation. Some studies incorporate weather impacts by making assumptions as to how traffic conditions react to weather while other studies use actual field observations.

This section presents a model implementation of weather impacts by using updated microscopic simulation parameters reflecting traffic conditions under inclement weather conditions. These parameters include:

- Free-flow speeds on roadways (mph);
- Maximum acceleration and deceleration rates (ft/s2);
- Gap acceptance for car-following, lane changing, and turning(s);
- Queue discharge headways at intersection(s); and
- Lost startup time at intersection(s).

For example, Lieu and Lin (2004) modified these microscopic traffic parameters by assuming reductions/augmentations to account for inclement weather conditions. The weather case, which consisted of wet and slushy weather/road surface conditions, had free-flow speed reduced by 20 percent and had queue discharge headway and lost startup time increased by 20 percent from those of the base condition. Three scenarios were analyzed in the study: 1) base case, 2) weather case, 3) weather case with signal retiming. After one hour of simulation, it was seen that speed reduced significantly in the weather base case. If average speed was 25 mph for the major-street demand of 1,450 vph in the base case then the average speed was 16 mph for a reduced major-street demand of 1,230 vph. Figure 3-12 shows the relationship of traffic speed and demand volume for 1 hour of simulation for the "weather without signal retiming" case and the "weather with signal retiming" case.

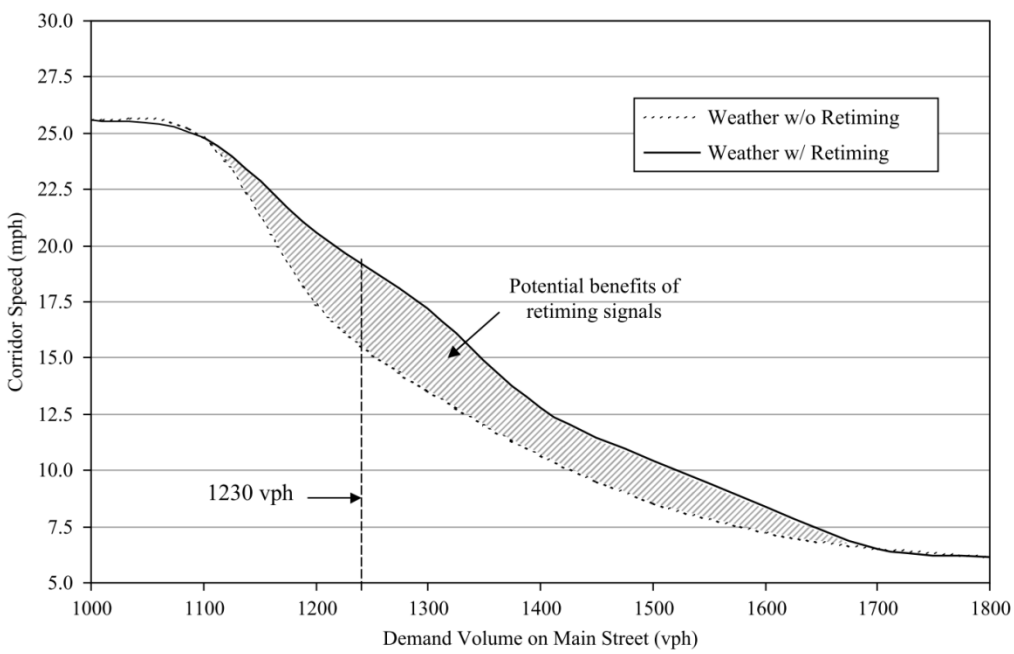


Figure 3-12 Relationship between Speed and Volume for Base and Weather Cases
(Source: Lieu and Lin, 2004)

Based on the analysis, implementing signal retiming specifically for inclement weather conditions improve traffic conditions if demand volumes on the major street are between 1100 vph and 1700 vph. As seen from Figure 3-13, demand volume of 1,230 vph coincides with a travel speed of 19 mph when signal retiming is put into effect for inclement weather conditions. For this demand volume, travel speed is 16 mph when signal retiming is not implemented.

A user can develop optimal signal timing plans for inclement weather conditions and evaluate those plans using microscopic models that reflect inclement weather conditions. For more information on this method please refer to Case Study 2.

4.0 Data Sources for Weather and Traffic Analysis

Using proper data sources can generate accurate and reliable results from a traffic analysis. For traffic analyses that focus on the impact of inclement weather conditions on the transportation system, weather and traffic data sources are required to complete the analysis. This section discusses the weather data sources, traffic data sources and Intelligent Transportation Systems (ITS) data sources available for weather-related traffic analysis.

4.1. Weather Data Sources

When conducting studies on the impact of inclement weather on traffic operations, collecting the proper weather-related data is essential. The most common weather-related data that is used in the evaluation of weather impacts on transportation are precipitation type, precipitation intensity, and visibility level. Weather Adjustment Factors (WAFs) are a function of these weather-related parameters. Agencies can use these WAFs within the weather module of DYNASMART-P and within microscopic modeling tools to assess the weather impacts on transportation. The advancement in technology has allowed weather-related data, necessary for impact assessment, to be available on the Web. This section presents examples of existing weather data sources that can be accessed online.

Clarus is an excellent source for accessing weather-related data for use by the transportation system. *Clarus* is designed to display current and forecasted weather-related data for a particular region Sensors that are used to collect traffic data vary among the different State DOTs. Therefore, the quality and format of the traffic data varies as well. Fortunately, *Clarus* provides users with data that share a common format. Convenience is a key characteristic of *Clarus*. Current users can access weather-related data for 38 States in the United States and 3 provinces in Canada, as shown in Figure 4-1.

Figure 4-1 Snapshot of *Clarus* Portal
(Source: http://www.clarus-system.com/)

Users can obtain detailed weather data such as air temperature, average wind direction, average wind speed, precipitation type, and precipitation rate from *Clarus* in either metric or English units. Incorporating the weather-related data available at *Clarus* can make data collection less time consuming and less costly as well.

In addition to *Clarus*, weather data is available online at the National Climatic Data Center (NCDC) website. This organization offers climate and weather information including temperature, precipitation, extreme weather events (e.g., hurricanes and tornados), and snow extremes. A snapshot of NCDC's webpage is shown in Figure 4-2.

Figure 4-2 National Climatic Data Center Website
(Source: http://www.ncdc.noaa.gov/oa/climateresearch.html)

From the NCDC website, users can access heavy rainfall frequencies provided by the National Oceanic and Atmospheric Administration's National Weather Service Hydrometeorological Design Studies Center. This weather data source allows user to be specific in their search for heavy rainfall frequency by providing options for data description (e.g., data type, units, and time series type) and location within a State. Weather data from NCDC can be obtained from the following link.

NCDC's Weather/Climate Data and Products
Available at: http://www.ncdc.noaa.gov/oa/climateresearch.html#dandp

Developed by the Department of Atmospheric, Oceanic and Space Sciences at the University of Michigan, UM Weather, shown in Figure 4-3, provides the public with up-to-date weather data on the Web.

Figure 4-3 UM Weather Homepage
(Source: http://cirrus.sprl.umich.edu/wxnet/)

Users of UM Weather can obtain city-by-city forecasts, conditions, warnings, and weather graphics for the United States. UM Weather allows users to receive live and daily pictures of weather conditions at over 700 locations in the United States and Canada. Users have access to over 150 weather sites (e.g., National Oceanic Atmospheric Administration, National Snow and Ice Data Center, and Midwestern Regional Climate Center) through UM Weather. Users can collect weather-related data from UM Weather at the link below.

UM Weather Data
Available at: http://cirrus.sprl.umich.edu/wxnet/

4.2. Traffic Data Sources

Transportation-related data is quite accessible currently because multiple traffic data sources are available through the Internet. This section discusses some Web-based data sources that can provide information on traffic data (e.g., speed and volume) commonly used in traffic analyses. It should be noted that analysts are not limited to these data sources, and that traffic data exists for different locations around the county. The purpose here, however, is to show examples of the types of Web-based data sources that are available.

Data collection through the Internet can begin with search engines such as Google. A user can do a search for "Highway Performance Monitoring System." Doing this will provide the link for the FHWA's Highway Performance Monitoring System (HPMS) website. The HPMS database

provides traffic data for statewide and nationwide highway systems. As part of HPMS, each State has permanent count stations, established in selected locations, that collect continuous 15-minute aggregated traffic counts. These traffic counts can be used in transportation planning models in order to obtain OD data for traffic analysis. Please refer to the HPMS website to access the available links to state HPMS websites. Link is provided.

Highway Performance Monitoring System
Available at: http://www.fhwa.dot.gov/policy/ohpi/hpms/index.cfm

Traffic engineers and researchers conducting weather-related traffic analyses involving the state of Virginia can collect traffic data from the Archived Data Management System (ADMS). ADMS provides data for such cases as planning and mobility performance measurement, decision support, and enhanced operational effectiveness (Center for Transportation Studies, 2010). A snapshot of the ADMS website is presented in Figure 4-4.

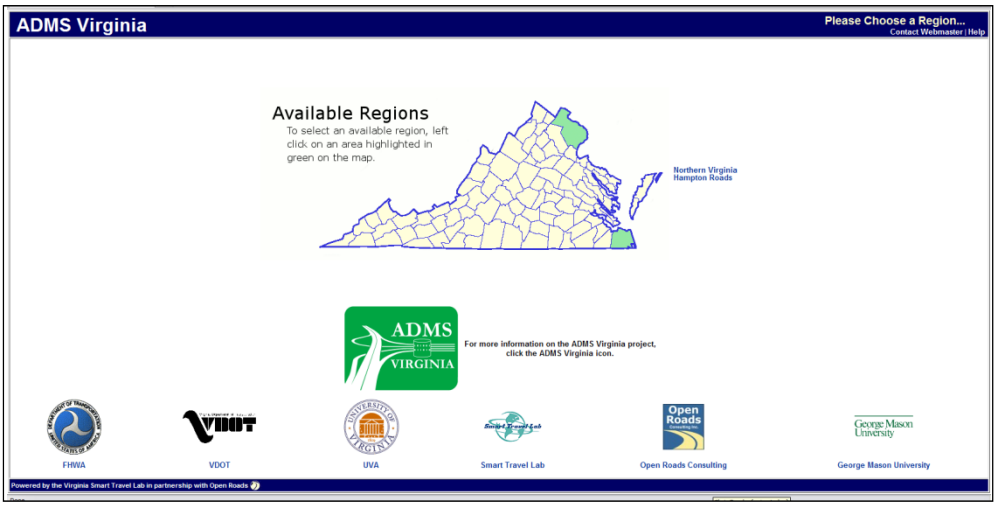


Figure 4-4 Archived Data Management System (ADMS) Homepage
(Source: http://adms.vdot.virginia.gov/ADMSVirginia/)

Authorized ADMS users can access traffic count and speed data in 24 hour periods from Northern Virginia and the Hampton Roads region of Virginia. ADMS uses permanent count stations to obtain traffic count data. These permanent count stations archive traffic counts by speed bins for a particular time interval (e.g., from 6:00 to 6:15, 85 vehicles counted for 55-60 mph bin). ADMS also uses sensors (e.g., loop detectors) that are embedded in the road to collect averaged speed data for a specific time interval. This Web-based system allows users to specify routes and dates when collecting traffic information.

In addition to traffic information, weather data can be easily accessed and downloaded online from ADMS. Users can specify weather conditions when collecting ADMS weather information. Available weather conditions include drizzle, rain, fog, haze, snow, thunderstorm, mist and others (Archived Data Management System 2010). ADMS can be accessed by the following link.

Archived Data Management System (ADMS)
Available at: http://adms.vdot.virginia.gov/ADMSVirginia/ NOTE: Users must obtain an account to use this site.

Analysts in California can access transportation-related data from the internet through the California Department of Transportation Performance Measurement System (PeMS). From this website, seen in Figure 4-5, users can access historic traffic data which were collected from a time period spanning over 10 years. From the 25,000 detectors, users can access real-time traffic data for volume, speed, and delay.

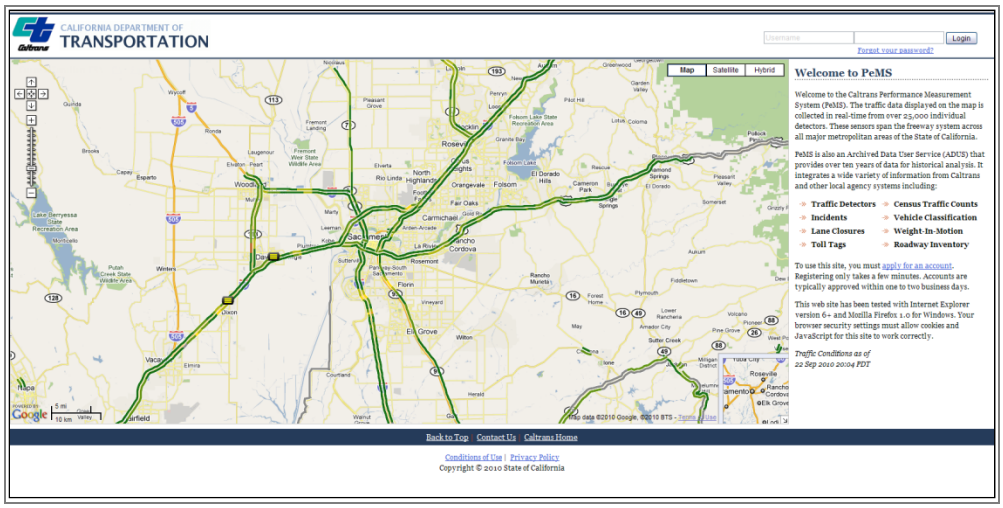


Figure 4-5 Performance Measurement System (PeMS) Homepage
(Source: http://pems.dot.ca.gov/?redirect=%2F%3Fdnode%3DState)

PeMS allows users to retrieve a wide range of transportation-related information from the California Department of Transportation and from local agencies, all in one stop. Such information includes: 1) incidents, 2) toll tags, 3) weight-in-motion, 4) vehicle classification, 5) census traffic counts, 6) lane closures, and 7) roadway inventory (California Department of Transportation, 2010). PeMS can be accessed by the link below.

Performance Measurement System (PeMS)
Available at: http://pems.dot.ca.gov/?redirect=%2F%3Fdnode%3DState NOTE: Users must apply for an account in order to obtain traffic data from PeMS.

A useful traffic data source for analysis in the Pacific Northwest is PORTAL which stands for Portland Oregon Regional Transportation Archive Listing. The PORTAL system contains a wide range of archived transportation-related data including the freeway loop detector data from Portland, OR to Vancouver, WA metropolitan area, incident data, freight data, transit data, and weather data (PORTAL, 2010). Figure 4-6 presents the homepage of PORTAL.

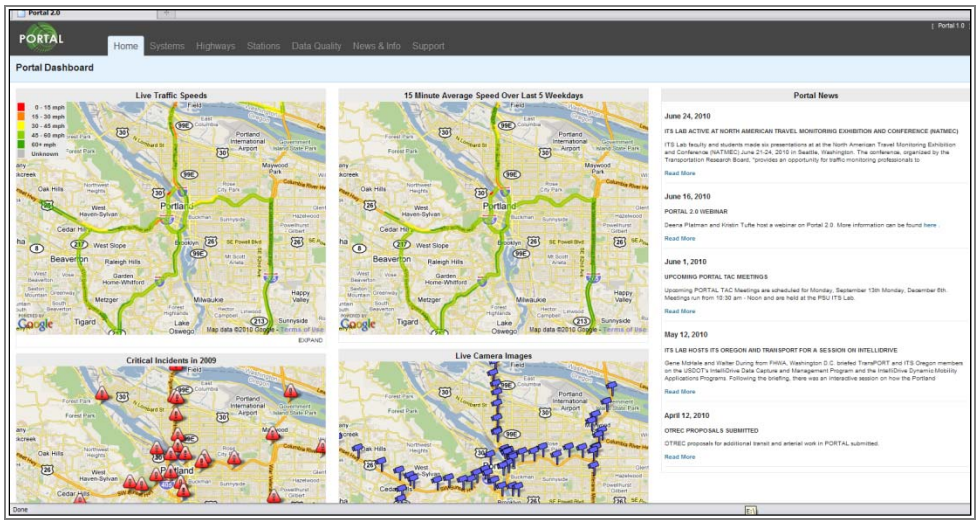


Figure 4-6 PORTAL Homepage
(Source: http://portal.its.pdx.edu/home/)

This data source provides daily statistics (e.g., total vehicle miles traveled, average travel time, and average travel speed) of highways in and around Portland, Oregon. An example of these daily statistics is shown in Figure 4-7 for I-5 North.

Figure 4-7 Daily Statistics for I-5 North
(Source: http://portal.its.pdx.edu/portal2.1/index.php/highways)

In conducting a microscopic analysis of traffic flow, users can use the live camera images from PORTAL to make visual observations of traffic flows on highways. Doing so could help users decide what needs to be accomplished to complete a successful analysis. For instance, users can conduct visual observations of headways during normal dry conditions and during inclement weather conditions. If they believe that headways significantly increase for inclement weather conditions from the visual observations then they can choose to calculate the actual changes in headways for their analysis. Data from PORTAL can be accessed at the following link.

PORTAL Traffic Data
Available at: http://portal.its.pdx.edu/home/

Transportation-related analyses should be conducted using data sources with an abundance of information, such as that made available by the Minnesota Department of Transportation (Mn/DOT). This State DOT provides traffic volume information consisting of annual average daily traffic (AADT) and heavy commercial average daily traffic (HCADT) (Minnesota Department of Transportation, 2010). Figure 4-8 presents a snapshot of the Mn/DOT traffic data webpage.

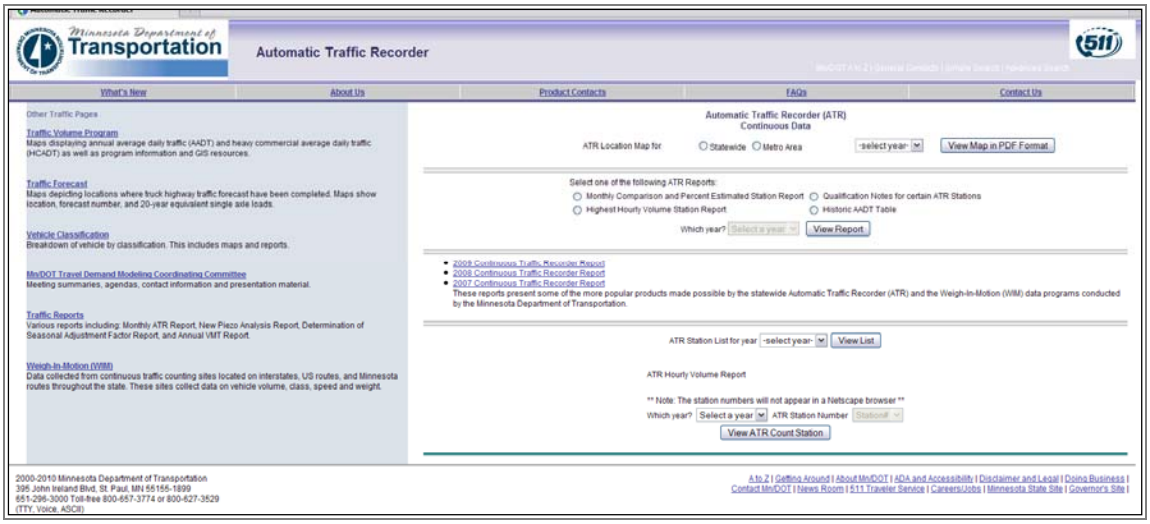


Figure 4-8 Minnesota Department of Transportation Traffic Data Webpage
(Source: http://www.dot.state.mn.us/traffic/data/atr/atr.html)

Minnesota also provides data obtained from continuous traffic counting sites that are located on interstates, municipal state-aid streets, and county-aid highways at different areas throughout the State. From these continuous traffic counting sites, users have access to data on volume, vehicle class, vehicle weight, and speed. Users can access the Minnesota Department of Transportation traffic data from the following link.

Minnesota Department of Transportation Traffic Data
Available at: http://www.dot.state.mn.us/traffic/data/atr/atr.html

In some cases, using archived databases from State DOTs is not sufficient to conduct transportation-related analyses. This may be due to the location that is being studied. The State DOT may not contain essential traffic information that would be relevant to those traffic analyses. Therefore in those cases, the collection of field data may be a suitable option.

4.3. Intelligent Transportation Systems Data Sources

Intelligent Transportation Systems (ITS) allows for traffic data collection through the use of wireless and wired electronic devices. This section discusses those ITS technologies that can provide users with traffic data, such as travel time, traffic speed, and vehicle location.

We are in a time where technology is constantly advancing, and ITS takes traffic data sources and weather data sources to a new technological level. Connected vehicles, a US Department of Transportation initiative, is designed to create a network that connects vehicles to infrastructure and wireless devices. It is proposed that connecting these three elements will enhance safety and mobility and reduce the negative effects of transportation on the environment.

The mobility applications for connected vehicles have the potential to provide detailed, real-time traffic data about traffic conditions to transportation managers, allowing them to optimize transportation system performance. Such optimization includes adjusting traffic signals and sending out maintenance personnel in the event of an emergency. Along with providing traffic data, connected vehicles will provide information on current weather and road conditions in small coverage areas such as mile-by-mile or block-by-block (Row, 2010).

Some short-term traffic analyses may be performed using real-time travel data acquired from ITS. These analyses may provide a better assessment of current traffic operations because they were conducted with consistent traffic data (i.e., data being collected for the same time period). Therefore, these analyses will not have to rely heavily on historic traffic data.

By using ITS-generated data, traffic management agencies may have better weather coverage for a particular location. These agencies may be able to estimate the precipitation intensity through the use of wiper sensors on vehicles. The frequency of these wipers is key here. If wipers are set at a fast rate to clear the fallen precipitation from windshields of the initiative's probe vehicles, then agencies may to able to assume that vehicles in the study area are experiencing severe inclement weather (e.g., heavy rain or snow).

For more information on the connected vehicles initiative, please refer to the following link.

Connected Vehicles
Available at: http://www.its.dot.gov/research/v2i.htm

Transportation agencies can obtain traffic information from INRIX. However, this data is not free of charge. INRIX, shown in Figure 4-9, is a traffic services company that provides transportation-related information to businesses and individuals located in North America and Europe.

Figure 4-9 INRIX Homepage
(Source: http://www.inrix.com)

Such information includes real-time and predictive traffic speed and travel times for major roadways (i.e., freeways and highways) and secondary roadways (i.e., arterials and side streets) (INRIX, 2010). Transportation-related information can be obtained for those who operate GPS-equipped vehicles (e.g., long-haul trucks and fleet vehicles) and who own consumer GPS-based devices (e.g., iPhone, iPad, Blackberry phones, and Android phones). For more information about the services provided by INRIX please refer to the following link.

When applicable, traffic information may be obtained from automatic vehicle location (AVL) technologies. This advanced traffic monitoring technology collects data from vehicles equipped with electronic tags (Tanikella *et al*., 2007). AVL allows for continuous collection of travel time data for each day of the year. Collecting travel time data in 24 hour periods is possible because AVL does not require manual recording of field data. Although AVL is heavily dependent on AVL devices (e.g., roadside antennas and roadside readers), it is a reliable source for travel time data collection.

Unlike AVL, Global Positioning System (GPS) involves locating objects that are not quite within reasonable reach. Transportation-related information (i.e., location and travel time) is collected from GPS-equipped vehicles that receive signals sent from the 24 satellites located in space (Turner *et al*., 1998). The collected data is sent to a storage computer located in a control center once the data collection process is completed. This method does not require making phone calls at checkpoints or manually recording information. Therefore, human error is smaller for data collection techniques that use GPS.

Travel time information collected from these ITS data sources can be essential in comparing the performance of a transportation facility during normal dry conditions and inclement weather conditions for weather-related transportation analyses. For additional information on AVL and GPS, please refer the Travel Time Data Collection Handbook shown below.

Travel Time Data Collection Handbook (1998)
Available at: http://www.fhwa.dot.gov/ohim/tvtw/natmec/00020.pdf

Engineers from Indiana Department of Transportation have raised the bar for the methods used to collect travel time data. Wasson, Sturdevant, and Bullock (2008) created a method that uses Bluetooth technology from cellular phones and other wireless devices to collect travel time data. Each wireless device has a unique digital signature which can be tracked by detectors located along the road. This method allows agencies to collect travel time for analysis purposes while also providing travel time information to motorists. For additional information on travel time data collection via Bluetooth please refer to *Real-Time Travel Time Estimates Using Media Access Control Address Matching* from the June 2008 issue of ITE Journal.

Real-Time Travel Time Estimates Using Media Access Control Address Matching
Available at: http://www.ite.org/membersonly/itejournal/pdf/2008/JB08F.pdf

5.0 Weather Responsive Traffic Operations and Management Strategies

Because the ideal weather condition (i.e., dry roadway, good visibility, no precipitation, and low winds) does not occur every day of the year, appropriate measures should be taken. Weather responsive traffic operations and management strategies have been developed to mitigate the impacts of inclement weather conditions. This section identifies existing traffic management strategies that would benefit from weather impact analysis.

A general concept of operations for weather responsive traffic management strategies consists of 1) basic operational objectives, 2) information gathering and impact assessment, 3) operational strategies, and 4) transportation outcomes. A flow chart of this Concept of Operations is presented in Figure 5-1.

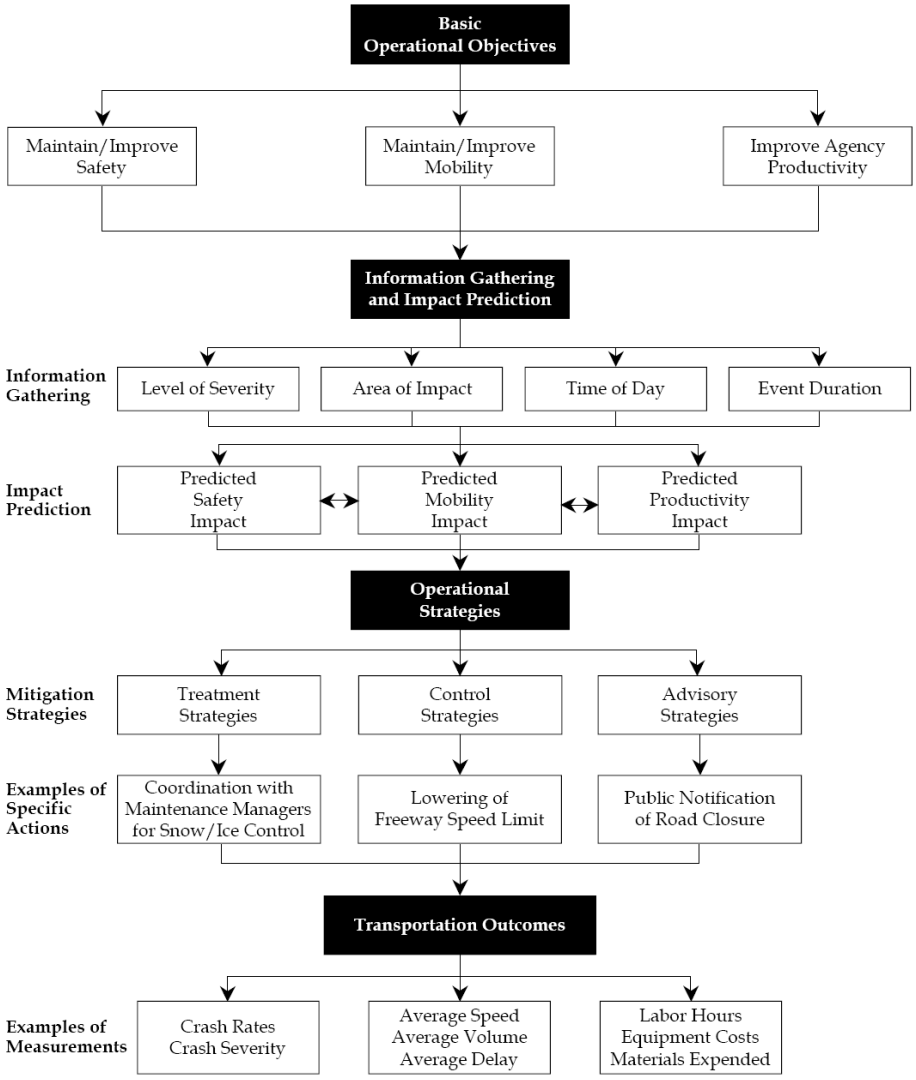


Figure 5-1 WRTM Concept of Operations Flow Chart
(Source: Cambridge Systematics, Inc., 2003)

Traffic management is regulated by basic operational objectives to ensure that safety, mobility, and agency productivity remain or improve to an acceptable condition. Gathering essential information, such as level of severity, area of impact, time of day, and event duration, is necessary in order to accurately assess weather impacts on safety, mobility, and productivity. By analyzing these impacts, traffic managers will have a better understanding of the influence of weather events on traffic operations and will be able to create appropriate mitigation strategies. Such strategies include treatment strategies, control strategies, and advisory strategies.

5.1. Advisory Strategies

Results of weather impact analyses can easily influence traffic advisory strategies. Let us say that a traffic analysis was conducted to determine the impact of rain on a road segment that includes a sharp curve. From the results, it was observed that the occurrence of crashes on this particular curve jumps up whenever there is heavy rain. Advisory strategies can be used to counteract the effect of inclement weather for that section of the road. These strategies are intended to provide pre-trip and en-route alerts and warnings which exist in the forms of passive warning systems, active warning systems, pre-trip road condition systems, and en-route weather alerts.

Travel time and delay information that are obtained from weather-sensitive traffic analysis can be used to improve existing traffic advisory strategies. Because of these weather-related analyses, the quality of the information that is shared to motorists through pre-trip and en-route alerts is higher. Their decisions on the aspects of the trip (e.g., trip value and route) can be made with higher confidence because they were given accurate travel time and delay information.

5.2. Control Strategies

In control strategies, roadway devices are altered to accommodate the change in traffic, weather, and pavement conditions. Examples of control strategies include speed management (e.g., variable speed limits, traffic signal control at signalized intersections, and ramp metering).

As part of speed management, variable speed limits are enforced on roadways in response to inclement weather conditions such as high winds and falling snow and rain. These variable speed limits will vary depending on weather, roadway, and traffic conditions.

Many weather-sensitive traffic analyses have shown that a significant number of motorists reduce their traveling speeds if they come upon severe inclement weather such as heavy rain or snow. A reduction in speeds can be due to poor visibility and/or decreased driver comfort levels when traveling in inclement weather. Traffic management agencies can incorporate this common trend acquired from weather-sensitive traffic analyses into the modification of their speed management strategies. If these agencies know that such a weather event as heavy rain will cause poor visibility and a reduction in the surface friction between the tires of a vehicle and the road then they can enforce variable speed limits suitable for motorists via dynamic message signs (DMS) and variable speed advisory signs. Because of inclement weather conditions, these enforceable speed limits may be significantly lower than the normal speed limit of a road, thereby causing a reduction in flow. This may not be a desired outcome from enforcing slower speed limits, but there would be larger reductions to flow if a motorist lost control of his vehicle when speeding on an icy road and crashed into surrounding vehicles. A traffic incident like this could cause a shutdown of lanes in that direction and ultimately cause a major disruption in the flow of traffic.

The information that can be taken from weather-sensitive traffic analyses can be beneficial to control strategies that involve signal timing. As previously discussed, weather-sensitive traffic analyses show that motorists reduce speeds when traveling in inclement weather, causing a reduction in flow. A reduction in flow is clearly seen at signalized intersections through saturation flow rate. This is defined as the number of vehicles per lane that can travel through a signalized intersection in an hour. When a significant amount of snow covers the roadway surface at a signalized intersection, vehicles stall in their initial movement before they can get through the signalized intersection. Due to reduced speed and this stalled initial movement, fewer vehicles can travel through the signalized intersection in an hour. With this knowledge, traffic management agencies can customize the traffic signal timing plans for inclement weather conditions. Doing so could allow more vehicles to get through the signalized intersection, thereby increasing saturation flow rate during inclement weather conditions.

Ramp control signals (also known as ramp metering) are used to regulate the traffic flow at freeway entrance ramps. Ramp meters detect when there are breaks in the platoons of vehicles. When there are adequate openings in these platoons, the ramp control signals allow vehicles to enter the freeway. Like signalized intersections, ramp control signals may be optimized if results from weather-sensitive traffic analyses are implemented in the ramp signal timing plans. Depending on traffic flow and inclement weather conditions, longer or short green times may be implemented into the ramp control signals.

5.3. Treatment Strategies

In treatment strategies, roadways are treated in order to reduce the effect inclement weather has on them. Strategies of this type often involve the interaction and cooperation of traffic management agencies and emergency agencies. Examples of treatment strategies include winter road maintenance (e.g., snow plowing to clear snow from roads and de-icing pavements) (Cambridge Systematics, 2003).

When weather-sensitive traffic analyses show that components of traffic operations, such as speed and flow, decline due to the accumulation of ice or snow on roads, traffic managers may be inclined to use the Maintenance Decision Support System (MDSS). MDSS is a tool developed by FHWA to help traffic managers make appropriate decisions on winter road maintenance. Such decisions are intended to improve treatment strategies with less financial strain. For example, Indiana DOT showed a savings of $12,108,910 in salt usage for the 2008-2009 winter season by using a MDSS (McClellan *et al*., 2009).

Along with MDSS, results from weather-sensitive traffic analyses can be an aid to traffic managers for their roadway treatment strategies. Some analyses may show that winter road conditions (e.g., icy roads and snow-covered roads) stall the initial movement of vehicles in a queue at a signalized intersection. This stall in movement is due to the reduction in surface friction caused by the winter road conditions. Results of these traffic analyses can support the treatment strategies (e.g., deicing roads with sand, salt, or other chemical de-icing agents) implemented by traffic management agencies. In other words, these traffic analysis results validate the purpose of having winter road maintenance strategies.

From weather-sensitive traffic analyses, transportation management agencies will be better informed about weather impacts on traffic operations. Some of these analyses show that queue length and delay increase because vehicles reduce their speeds significantly when traveling on icy or snow-covered roads. Using this information, traffic management agencies can be better

prepared in handling such weather events. They will be able to estimate the manpower and labor that is required to treat roads so that the flow of traffic does not worsen significantly.

6.0 Case Study

6.1. An Implementation of DYNASMART in Hampton Roads, VA. – Mesoscopic Simulation

6.1.1. Case Study Summary

Recent research has shown that inclement weather may negatively affect many traffic parameters (e.g., traveling speeds, travel time, and roadway capacities), roadway safety, and vehicle operability. The extent to which weather affects these parameters has not been well quantified. Inclement weather is sporadic and often has a sudden onset; if sensors are not already in place, it is difficult to capture the effects of inclement weather. To this end steps have been taken to quantify and model the effects of weather on traffic operations.

This study was conducted to develop models in DYNASMART-P that would estimate and predict the impact of inclement weather on traffic operations. DYNASMART-P, a mesoscopic traffic simulation tool, was selected for the study because it consists of a recently developed weather module. The required inputs consisted of data for the traffic parameters speed and density, data for segment types (e.g., ramp, merge, diverge, and weave), and weather-related data (e.g., precipitation type, precipitation intensity, and visibility). Results of this study showed that using Weather Adjustment Factors (WAFs) would provide smaller overestimations of speed in inclement weather.

6.1.2. Description of the Study

Hampton Roads, Virginia, located in Southeastern Virginia, is comprised of 16 diverse localities and is home to 1.6 million people. In 2006, 26 million hours of delay were caused by vehicles slowed or stopped in Hampton Roads traffic due to congestion and lack of capacity. Inclement weather can greatly exacerbate the safety problems and congestion delay of the region, which makes it a prime location to assess the potentially negative effects of inclement weather.

It is noted that the primary focus of the DYNASMART-P weather module was realizing the effect that weather has on supply parameters and user response to weather-informed control devices (e.g., traffic signals, VMS, etc.) and weather information. As such, this case study does not cover demand adjustment. For more information on how weather might affect demand parameters and how users can modify their demands to reflect the effect of weather, refer to Section 3.2.4.2.

The study network is composed of approximately 197 miles of freeway segments that service Hampton Roads on I-64, I-564, I-264, and I-664.

The network was coded into DYNASMART-P using coordinates and geometries already collected for a previous study using DynaMIT. The DYNSMART-P Hampton Roads Network is depicted in Figure 6-1.

Figure 6-1 Hampton Roads DYNASMART-P Network

DYNASMART-P uses a macroscopic relationship between speed and density to simulate vehicle movement. The single regime model is applicable to arterial models and the dual regime model is applicable to freeway models due to capacity differences. For this case study, the dual regime model is used. The mathematical representations of this relationship are as follows:

Dual Regime Model:

$$v_i = u_f \qquad 0 \le k_i \le k_{brkpnt} \tag{6-1}$$

$$v_i - v_0 = \left(v_f - v_0\right) \cdot \left[1 - \frac{k_i}{k_{jam}}\right]^{\alpha} \qquad k_{brkpnt} \le k_i \le k_{jam} \tag{6-2}$$

Where

v_i = speed on link i	k_i = density on link i
v_f = speed-intercept	k_{jam} = jam density on link i
u_f = free-flow speed on link i	α = power term
v_0 = minimum speed on link i	k_{brkpnt} = breakpoint density

To initiate use of the weather module, a user must first create the weather.dat file in their project directory. This file describes either an across-the-board (network-wide) or a link-specific weather condition (link-specific weather information will take precedence over network-wide weather information). The general format of the weather.dat file and the weather.dat file of the Hampton Roads test case are shown in Figure 6-2.

```
1   (Network wide weather condition exist, (0 otherwise))
0.5  0.1  0  0  120  (Network Weather Conditions: visibility=.5mile, rainfall=0.1 in/hr, snowfall = 0 in/hr, duration = first 2 hours (0 to 120 minutes))
3  (3 link specific weather conditions exists)
1   4042   4087  2    (link condition 1: on link connecting node 4042 to node 4087 has 2 weather conditions)
10  40   1.0   0.1   0 (between minutes 10 and 40, visibility = 1.0mile, rainfall =0.1in/hr, snowfall=0in/hr.)
41  60   0.5   0.2   0 (between minutes 41 and 60, visibility = 0.5mile, rainfall =0.2in/hr, snowfall=0in/hr.)
2  4084    4042  1  (link condition 2: on link connecting node 4084 to node 4042 has 1 weather condition)
10   80   0.5   0   0.1 (between minutes 10 and 40, visibility = 0.5mile, rainfall =0in/hr, snowfall=0.1in/hr
3  3826    581 1 (link condition 3: on link connecting node 3826 to node 581 has 1 weather condition)
0   20   1.0   0   0  (between minutes 0 and 20, visibility = 1.0mile, rainfall =0in/hr, snowfall=0.0in/hr

1
0.5     0.02    0       90      150
```

Figure 6-2 Description of Weather Data in DYNASMART-P

Table 6-1 Weather Sensitive Demand Parameters

Input Data	Traffic Properties	Notes
Traffic Flow Model	1. *Speed-intercept,* (mph) 2. Minimal speed, (mph) 3. Density break point, (pcpmpl) 4. Jam density, (pcpmpl) 5. Shape term alpha	Italic properties are for dual regime model only
Link	6. Maximum service flow rate 7. Saturation flow rate 8. Posted speed limit adjustment margin	
Signal Control	Cycle length, offset, green, amber, max green, min green	All same units, (sec)
Left-turn Capacity	9. g/c ratio	
2-way Stop Sign Capacity	10. Saturation flow rate for left-turn vehicles 11. Saturation flow rate for through vehicles 12. Saturation flow rate for right-turn vehicles	All same units, (vph)
4-way Stop Sign Capacity	13. Discharge rate for left-turn vehicles 14. Discharge rate for through vehicles 15. Discharge rate for right-turn vehicles	All same units, (vph)
Yield Sign Capacity	16. Saturation flow rate for left-turn vehicles 17. Saturation flow rate for through vehicles 18. Saturation flow rate for right-turn vehicles	All same units, (vph)

Once the weather conditions are specified, the users are able to implement the weather module to calculate the effects of inclement weather. Weather module effects take the form of a weather adjustment factor (WAF). Normal weather parameters are multiplied by a WAF in order to calculate inclement weather parameters. Northwestern University identified 18 supply and operational parameters present in the DYNASMART-P framework that could be affected by inclement weather. These parameters are described in Table 6-1.

For each of the parameters above, a weather adjustment factor (WAF) was calculated. WAF is calculated as:

$$F_i = \beta_0 + \beta_1 \times v + \beta_2 \times r + \beta_3 \times s + \beta_4 \times v \times r + \beta_5 \times v \times s \qquad (6\text{-}3)$$

Where,

Fi = WAF for parameter i
v = visibility (miles)
r = precipitation intensity of rain
s = precipitation intensity of snow
β1, β2, β3, β4, β5 = coefficients

Under inclement weather, the supply parameters are calculated as follows:

$$F' = F_o \times F_i \qquad (6\text{-}4)$$

Where,

F' = weather adjusted parameter
Fo = normal weather parameter
Fi = weather adjustment factor

The coefficients for the above equations are described in the WAF.dat control file. The general format of this file and the Hampton Roads WAD.dat file are presented in Figure 6-3. Note that because the Hampton roads network is a freeway system containing no traffic control devices, many of the supply/operational parameters are not applicable, and so weather would not have any effect on them. The WAF.dat table allows the user to implement the weather module either generally or specifically. For example, to use the module, generally the user would need to calculate the coefficients of each supply parameter by observing a wide variety of weather conditions and performing some regression analysis. Therefore, no matter what amount of precipitation (rain and snow) and level of visibility the user plugs into the weather.dat table, the calculated coefficients would still be applicable. If the user is only interested in observing the effects of a very specific weather condition, that user could collect traffic information for just that weather condition. Using this newly collected data, the user could calculate the weather adjustment factor for each parameter as:

$$F_i = \frac{F'}{F_o} \qquad (6\text{-}5)$$

These WAFs can then be plugged into the WAF.dat table in the β_0β0 position for each parameter and the other coefficients can be set to zero which would result in $F_i = \beta_0.\beta_0$. The caveat to this approach is that the WAFs calculated are only good for the specific weather situation from which they were derived.

```
1   0.91   0.009   -0.404   -1.455   0   0 (speed intercept weather adjustment factor:
β0=.91,β1=0.009, β2=-.404, β3=-1.455, β4=0, β5=0)
2   1   0   0   0   0   0 (minimal speed weather adjustment factor: β0=0, β1=0, β2=0, β3=0, β4=0,
β5=0)
3   .83   0.017   -0.555   -3.785   0   0 (Density Breakpoint weather adjustment factor:
β0=.83,β1=0.017, β2=-.555, β3=-3.785, β4=0, β5=0)
4   1   0   0   0   0   0 (Jam Density weather adjustment factor: β0=0, β1=0, β2=0, β3=0, β4=0,
β5=0)
5 1   0   0   0   0   0 (Shape Term weather adjustment factor: β0=0, β1=0, β2=0, β3=0, β4=0, β5=0)
6   0.85   0.015   -0.505   -3.932   0   0 (Maximum Service Flow Rate weather adjustment
factor: β0=0.85, β1=0.015, β2=-0.505, β3=-3.932, β4=0, β5=0)
7   0.91   0.009   -0.404   -1.455   0   0 (Saturation Flow Rate weather adjustment factor:
β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
8   0.91   0.009   -0.404   -1.455   0   0 (Posted Speed Limit Adjustment Margin weather
adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
9   0.91   0.009   -0.404   -1.455   0   0 (g/c ratio weather adjustment factor: β0=0.91,
β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
10   0.91   0.009   -0.404   -1.455   0   0 (Saturation Flow Rate for left turn 2- way stop
weather adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
11   0.91   0.009   -0.404   -1.455   0   0 (Saturation Flow Rate for thru 2- way stop
weather adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
12   0.91   0.009   -0.404   -1.455   0   0 (Saturation Flow Rate for right turn 2-way stop
weather adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
13   0.91   0.009   -0.404   -1.455   0   0 (Discharge Flow Rate for left turn weather
adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
14   0.91   0.009   -0.404   -1.455   0   0 (Discharge Flow Rate for thru weather
adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
15   0.91   0.009   -0.404   -1.455   0   0 (Discharge Flow Rate for right turn weather
adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
16   0.91   0.009   -0.404   -1.455   0   0 (Saturation Flow Rate for left turn 4-way stop
weather adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
17   0.91   0.009   -0.404   -1.455   0   0 (Saturation Flow Rate for thru 4-way stop
weather adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
18   0.91   0.009   -0.404   -1.455   0   0 (Saturation Flow Rate for right turn 4-way stop
weather adjustment factor: β0=0.91, β1=0.009, β2=-0.404, β3=-1.455, β4=0, β5=0)
```

(a) General WAF.dat file

```
1      0.910  0.009  -0.404 -1.455 0      0
2      1      0      0      0      0      0
3      0.830  0.017  -0.555 -3.785 0      0
4      1      0      0      0      0      0
5      1.005  0      0      0      0      0
6      0.850  0.015  -0.505 -3.932 0      0
7      0.910  0.009  -0.404 -1.455 0      0
8      0.910  0.009  -0.404 -1.455 0      0
9      1      0      0      0      0      0
10     1      0      0      0      0      0
11     1      0      0      0      0      0
12     1      0      0      0      0      0
13     1      0      0      0      0      0
14     1      0      0      0      0      0
15     1      0      0      0      0      0
16     1      0      0      0      0      0
17     1      0      0      0      0      0
18     1      0      0      0      0      0
```

(b) Hampton Roads WAF.dat file

Figure 6-3 Snapshots of WAF.dat files

From Figure 6-3, rows 1 to 18 represent the weather-sensitive demand parameters shown in Table 6-1. The order in which these parameters are presented in Figure 6-3 and Table 6-1 are the

same. From both, row 1 is the speed intercept, row 2 is the minimal speed, and so on. Each row from Figure 6-3 consists of six columns that fall after the first column on the far left. These columns represent the coefficients in the following order: β0, β1, β2, β3, β4, and β5.

Once the weather files are created, the user can execute DYNSMART-P for a specified planning horizon. As shown in Figure 6-4, the program simulates the movements of vehicles using the speed-density relationships and link-based constraints (speed limits, saturation flow rates, etc.) using any weather information that has been specified by the user.

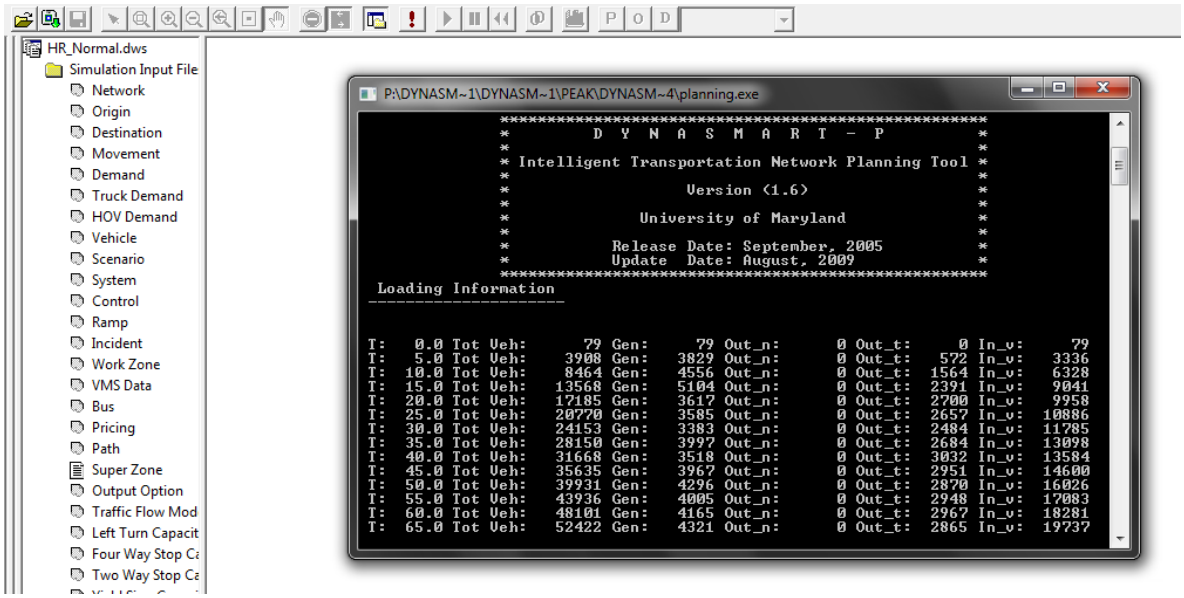


Figure 6-4 DYNSMART-P Program

The outputs of the simulation can be evaluated to determine the relative effects of weather. For example, users can compare the speeds, densities, volumes, etc. of normal weather and inclement weather simulations (keeping all other factors such as planning horizon, OD, traveler population characteristics constant). The relative difference in performance measures between the normal weather and inclement weather simulations would reflect how much the simulated weather condition affects traffic flow and behavior.

6.1.3. Demand Adjustment

An example simulation was performed for Hampton Roads. A demand-based analysis was also used in order to compare the effectiveness of the supply-based adjustments versus demand-based adjustments. The University of Virginia has taken a critical look at the effects of weather on traffic demand. A study entitled "Probabilistic Modeling of Inclement Weather Impacts on Traffic Volume" observed the relative effects of weather, particularly rain and snow, on traffic volumes (Samba and Park, 2009). The study analyzed traffic volumes that occurred under inclement weather, comparing to average volumes that could be expected under normal weather conditions. From this analysis, it was observed that the likelihood of traffic volumes declining as a result of inclement weather increased as precipitation intensity increased and that the magnitude of volume reduction was time-dependent. These observations resulted in a probabilistic method for estimating traffic demand reductions at a given hour of the day based on precipitation intensity categories (light, less than .25 in/Hr, versus heavy, greater than .25 in/Hr)

for both rain and snowfall conditions. Please refer back to Section 3.2.4.2 for the traffic volume reduction procedure and example problem.

A summary of the weather-related impacts on traffic demand is provided in Table 6-2.

Table 6-2 Weather Impacts on Traffic Demand

Weather Condition	Probability of Weather Impacted Volumes	Volume Reduction Change	Average Volume Reduction
Light Rain	16.6%	1.0% to 6.3%	2.32%
Heavy Rain	31.3%	3.1% to 4.4%	3.75%
Light Snow	76.0%	10.6% to 56.2%	28.80%
Heavy Snow	42.9%	4.7% to 30.4%	13.30%

(Source: Probabilistic Modeling of Inclement Weather Impacts on Traffic Volume, Samba and Park, 2009)

It should be noted that the demand-based method has not yet been validated for its ability to reflect real-world traffic behaviors such as travel speed and volumes.

6.1.4. Analysis and Results

The evaluation process for the DYNASMART-P weather module is as follows. First, real world speed data for light rain and heavy rain days were gathered for 10 traffic stations located to the north, south, and west of the I-264 interchange. Then, three simulations were made for each of these weather types (Figure 6-5).

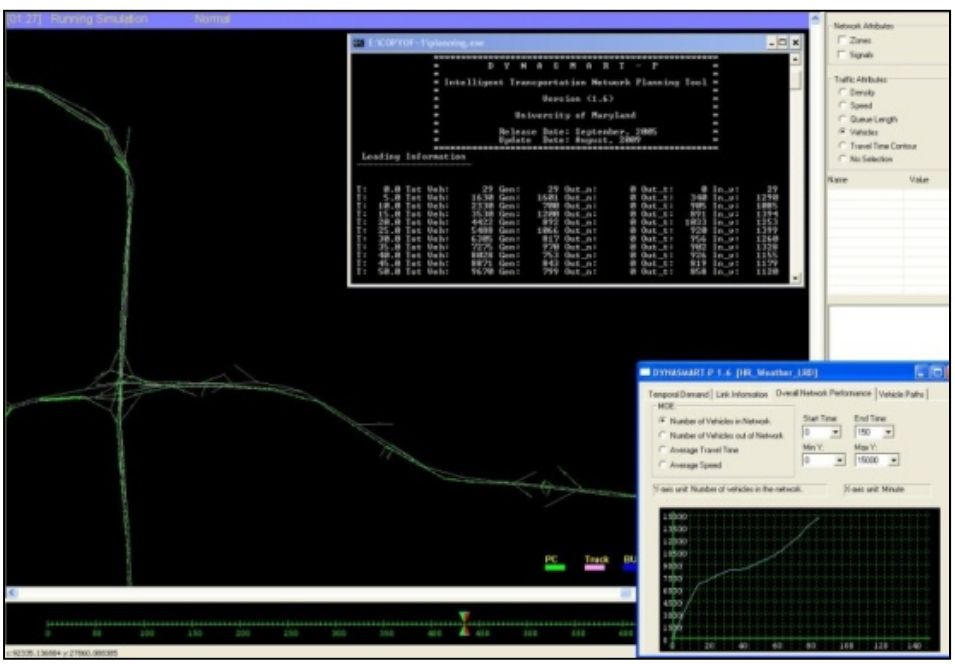


Figure 6-5 Hampton Roads DYNASMART-P Program Snapshot

The lower right window in Figure 6-5 shows a curve representing the number of vehicles in the network (y-axis) for a duration period of 150 minutes (x-axis). The maximum number of vehicles present in the network is approximately 150,000. The right toolbar consist of network attributes (e.g., zones and signals) and traffic attributes (e.g., density, speed, queue length, and vehicles).

The simulation modified those normal weather parameters using the weather adjustment factors of the DYNASMART-P weather module. For this simulation, an across-the-board weather scenario that occurred for the entire simulation horizon was specified. The primary supply parameters that are applicable to this network and were adjusted for weather impacts are the components of the traffic flow model (speed-intercept, minimal speed, and posted speed limit adjustment margin). Additional link-specific parameters like maximum service flow rate and posted speed limit adjustment margin were also modified with the weather adjustment factors. The last simulation reduced the historical OD demands using the probabilistic traffic demand reduction method based on the precipitation category and time of day. All simulation and real-world data were for the hours of 2:00 p.m. to 5:00 p.m. The root mean square errors (RMSE) of speeds were used to assess the ability of each simulation type to reflect real-world data accurately. RMSE can be calculated as:

$$\sqrt{\frac{\sum_{i=1}^{n}\left(x_{1,i}-x_{2,i}\right)^2}{n}} \tag{6-6}$$

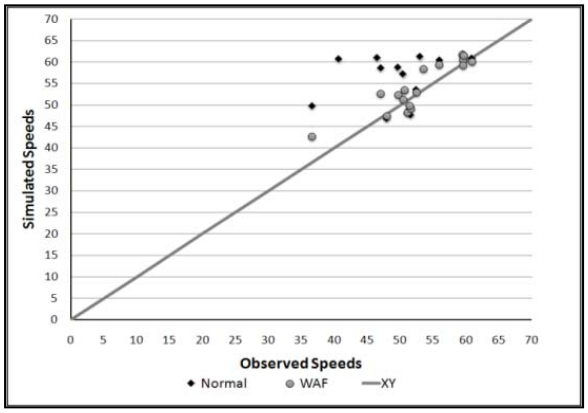
Where,

$x_{1,i}$ = actual value for time i
$x_{2,i}$ = simulated value for time i
n = number of observations

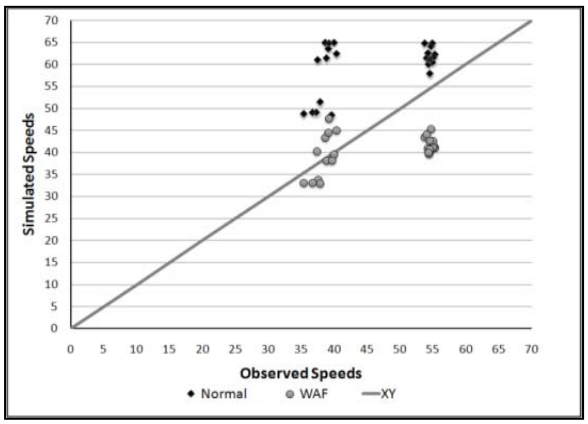
Table 6-3 presents calculated RMSE for the observed and simulated speeds. Both light and heavy rain days are represented. The WAF module consistently shows the least error in simulated speeds for both light and heavy rain days with RMSE of 14.2 and 14.7 for the two scenarios, respectively. The average normal weather parameter case had RMSE of 15.7 and 17.1 for light and heavy rain days. Adjusting demand creates minor increases in the error of simulated mobility measures relative to using normal parameters. The reduction in error due to WAF is greater in the heavy rain case than in the light rain case; we can expect that weather would have the greatest perceived (by drivers) and observed (in terms of supply parameter changes) effect at greater intensities. This suggests that the more intense (heavier precipitation) or extreme (snow versus rain, for example), the less the variation in the magnitude of individual errors when using the WAF module.

Table 6-3 RMSE between Observed and Simulated Speeds

Weather Condition	Average Normal Weather	Parameter Speed Average Demand	Adjusted Speeds Average WAF Module
Light Rain	15.7	15.9	14.2
Heavy Rain	17.1	18.2	14.7



(a) Light Rain



(b) Heavy Rain

Figure 6-6 Simulated and Observed Speeds

In terms of the simulated speeds, on average, using normal parameters, or the demand-adjusted case, to assess a light rain day would result in overestimation of speeds by approximately 2 miles per hour, whereas using the weather adjustment factor would lead to speed overestimations by approximately 1 mile per hour. For heavy rain, simulations with weather adjustment factors reduced the error between simulated and observed speeds by approximately 33 percent compared to the errors of the normal parameter case. Figure 6-6 shows that for light rain conditions, the WAF module is more accurate in representing observed values than normal weather parameters. For heavy rain conditions, the WAF module is again shown to be better than using normal parameters, especially at lower speeds. It should be noted that at higher speeds, the WAF module is less precise, suggesting that more calibration could increase the accuracy of the model when simulating heavier precipitation.

6.1.5. Conclusions

The following presents the conclusions discovered in the case study.

Hampton Roads Case Study – Conclusions
▪ Smaller overestimations of speeds in light rain were seen with the use of weather adjustment factors (WAFs). WAFs overestimated speeds by approximately 1 mile per hour while using normal parameters or the demand adjusted case overestimated speeds by approximately 2 miles per hour. ▪ When compared to the errors observed in the normal parameter case, simulations conducted with the use of WAFs for heavy rain conditions reduced the error between the simulated and actual speeds by about 33 percent. ▪ At higher speeds the WAF module is less precise. This suggests that simulating heavy precipitation with higher accuracy could be performed.

6.1.6. Guidance

Those who are interested in conducting their own weather-related transportation study, similar to the Hampton Roads case study, can follow the procedure presented in this section. A review of this procedure follows. Users can begin their study by collecting all the necessary input data. This includes traffic data (e.g., speed and density), segment data, and weather-related data (e.g., precipitation type, precipitation intensity, and visibility). Assuming that data calibration can be performed within the modeling tool, input data should be calibrated so that simulation results do not include any major errors. Doing so allows users to assume and ensure that traffic and weather data are valid. Users can then create a weather.dat file and specify the weather types that are involved in their analysis. Afterwards, users can begin the process to calculate the impacts of inclement weather using the weather module in DYNASMART-P.

In the analysis, three simulation runs are conducted for each precipitation type. For the first simulation run, users should convert the calculated normal weather parameters to the DYNASMART-P format. In the second simulation run, users can adjust the normal weather parameters by multiplying them with the Weather Adjustment Factors (WAFs) from the DYNASMART-P weather module. For the third simulation, users can use the probabilistic traffic demand reduction method to estimate the reduced OD demands, although this method has not been validated in terms of its ability to reflect with accuracy the reduced demand caused by inclement weather.

Using the weather module in DYNASMART-P, agencies could have more accurate estimations and predictions of real-world traffic parameters during inclement weather conditions. However, further calibration and validation of the WAFs might be required to ensure accurate traffic estimation and prediction under inclement weather conditions. It is expected this would be achieved in the near future by analyzing archived weather data from the Clarus initiative and/or the connected vehicles initiative, and conducting more case studies incorporating inclement weather.

6.2. Traffic Signal Operation under Inclement Weather – Signal Optimization and Microscopic Traffic Simulation

6.2.1. Case Study Summary

Traffic flow at signalized intersections is influenced by time-dependent factors such as time of day and day of week. Generally, traffic flow is at its busiest during peak hours of the day. Traffic conditions can worsen when an additional variable such as inclement weather is added to mix. Depending on the severity of the inclement weather condition, traveling speeds can decrease,

causing saturation headway to increase and ultimately causing an increase in saturation flow (Perrin *et al*., 2001). These traffic conditions are known to occur at signalized intersections during inclement weather, and yet the timing of the signals is often operated under normal weather and traffic behavior.

Macroscopic and microscopic modeling tools (TRANSYT-7F, SYNCHRO, CORSIM, and SimTraffic) were used to develop and evaluate weather-specific signal timing plans for four corridors in New England. The following parameters were required for calibration: saturation headway, saturation flow rate, lost startup time, free flow speed, and headway factor. The study shows that weather-specific signal timing plans will provide operational benefits when inclement weather last for longer periods (e.g., 1 hour and 2 hours).

6.2.2. Description of the Study

Sadek and Agbolosu-Amison conducted a case study with two main objectives: 1) analyze the impact of inclement weather at signalized intersections, and 2) quantify the likely operational benefits of signal retiming specifically tailored for inclement weather conditions. The latter is the focus of this discussion. In the second half of the case study, a total of four corridors (two from Vermont and two from Connecticut) were analyzed. Each corridor selected needed to have at least 3 but no more than 10 intersections. The w corridors from Vermont (Dorset Street and Vermont Route 15) have 10 intersections each while the 2 corridors from Connecticut (Storrs Road and Hale Road) has 5 intersections each.

Figures 6-7 and 6-8 display the locations of the intersections for the two Vermont corridors. Both corridors are located from one end of Arrow A to one end of Arrow B. Dorset Street, which has a total length of 1.725 kilometers (1.08 miles), consists of eight signalized intersections and two unsignalized intersections. The signalized intersections are being operated by actuated controllers. Dorset Street provides access to nearby businesses and allows the through traffic movement to continue through the City of South Burlington The segment that was selected from Vermont Route 15, located in Chittenden County, Vermont, is 5.836 kilometers (3.63 miles) long and is made up of 10 signalized intersections; all of which are operated by actuated controllers. Vermont Route 15 provides access to businesses in the area and accommodates the traffic movement through Colchester.

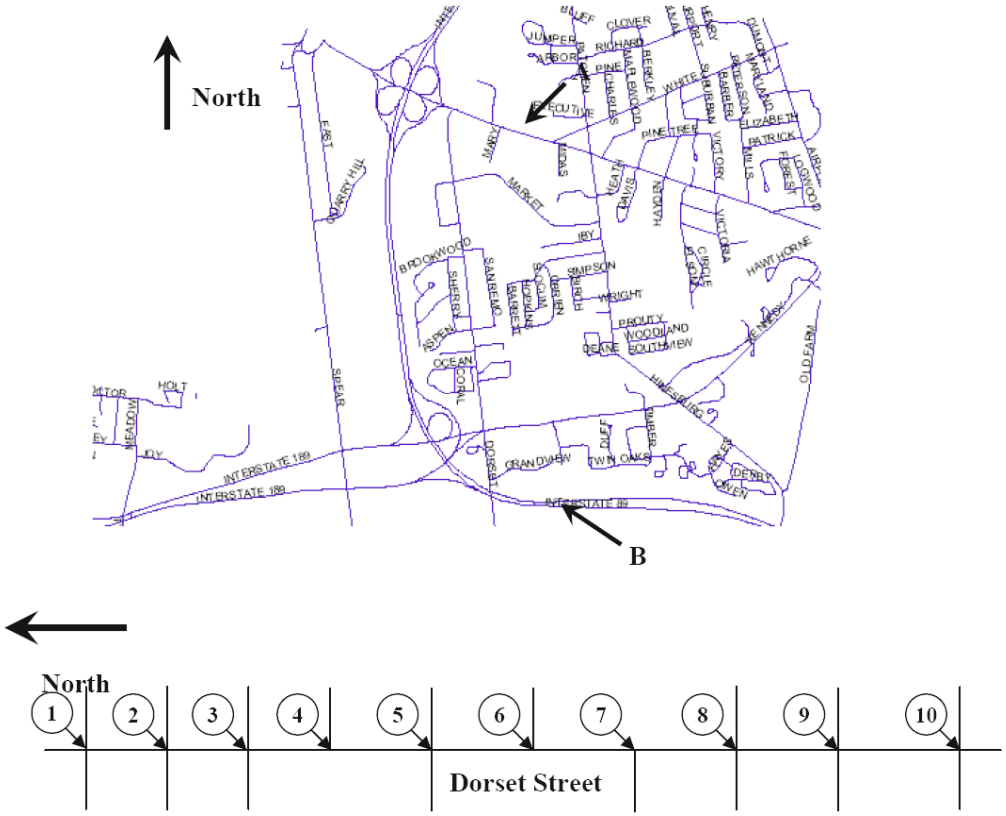


Figure 6-7 Dorset Street
Notes: Intersections 1 and 10 are isolated, fully-actuated intersections.
Intersections 2, 3, 4, 5, 8 and 9 are semi-actuated and coordinated.
Intersections 6 and 7 are unsignalized.
(Source: Sadek and Agbolosu-Amison, 2004)

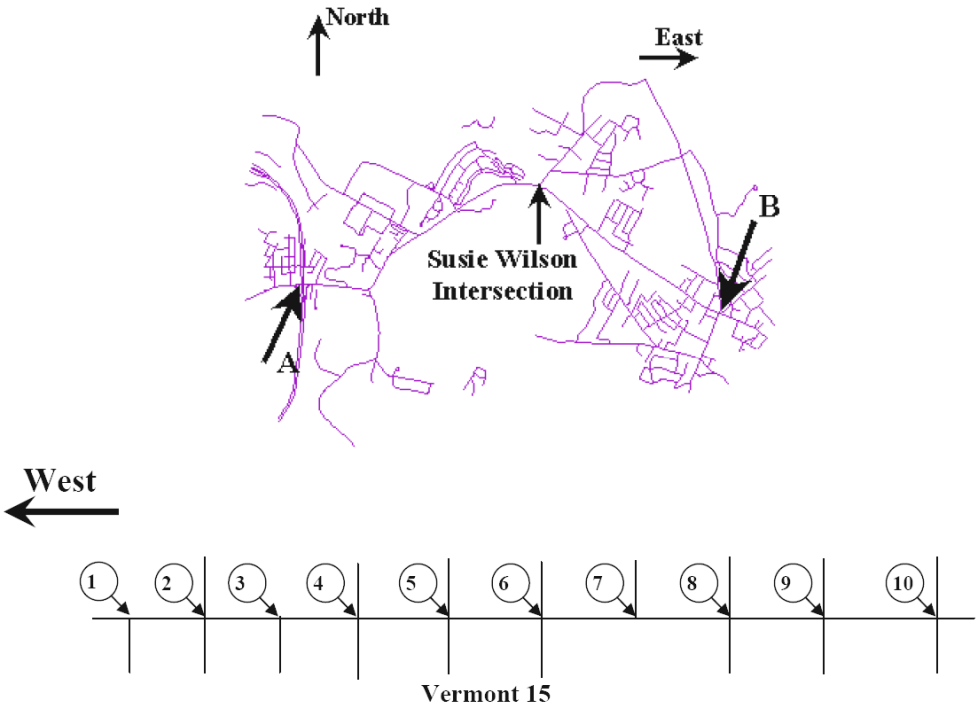


Figure 6-8 Vermont Route 15
Intersections 1 to 10 are actuated signalized intersections.
Intersections 1 to 8 are coordinated.
Intersections 9 to 10 are uncoordinated.
(Source: Sadek and Agbolosu-Amison, 2004)

In order to assess the likely benefits of implementing "special" signal timing plans that take account of inclement weather conditions, Sadek and Agbolosu-Amison (2004) used two modeling tools in the case study. The first tool was used to develop the signal timing plans, and the second tool was used to evaluate the feasibility of incorporating these plans into action. Two macroscopic traffic signal timing optimization models (TRANSYT-7F and SYNCHRO) and two microscopic simulation models (CORSIM and SimTraffic) were used in the study to meet the objectives. The microscopic simulation models were used to evaluate the signal plans.

6.2.3. Analysis and Results

Data were required for the development and calibration of these simulation models. The case study consisted of traffic data that were collected during the PM peak hour period between 4 pm and 5 pm for the study's six different weather conditions (dry, wet, wet and snowy, wet and slushy, slushy in wheelpaths, and snowy and sticky) (Sadek and Agbolosu-Amison, 2004). The required data model development and calibration included the following:

Required Data for Model Development and Calibration
▪ Traffic Flow Data: This includes data on total volumes, turning movements at the intersections, and traffic speed information. These data were collected between the hours of 4:00 p.m. and 5:00 p.m. for each intersection using a digital video camera recorder and a manual traffic counter. ▪ Geometric Data: This included information on the number of lanes, spacing between intersections and driveways, and lane channelization. ▪ Traffic Control: This refers to information about the type of traffic control at each intersection, traffic signal timing, and coordination plans. These data were collected using a stopwatch. For the signal timing parameters for actuated controllers, averages of 10 signal cycles were computed. ▪ Saturation Headway and Lost Startup Time: Saturation headways and lost startup times were collected from the project site and used in developing and calibrating the simulation models for the "dry" weather condition.

(Source: Sadek and Agbolosu-Amison, 2004)

Specific performance measures were incorporated in the analysis for the evaluation of the "special" signal timing plans. These include: 1) total travel time, 2) maximum queue length (MQL), and 3) average maximum back of the queue (AMBQ). The AMBQ measures the average number of vehicles in a queue including the vehicles that arrive at the back of the queue during the green time of a cycle.

Developing a base model is necessary for proper comparison of the traffic conditions for the six different weather conditions. This case study set the "dry" weather condition as the base condition. A total of 16 base models were developed using TRANSYT-7F and SYNCHRO. After developing the base models, the next step in the procedure was calibrating the model parameters so that the model output matched field conditions. Table 6-4 presents the adjusted parameters for the four simulation models. Please refer to the following links for additional information on the four models used in the study:

TRANSYT-7F, SYNCHRO, CORSIM, and SimTraffic Information
Available at: TRANSYT-7F and CORSIM http://mctrans.ce.ufl.edu/ SYNCHRO and SimTraffic http://www.trafficware.com/simtraffic7.html

Table 6-4 Parameters Adjusted During Calibration of Simulation Models

Parameter	CORSIM	SimTraffic	TRANSYT-7F	SYNCHRO
Saturation Headway	•			
Saturation Flow Rate			•	•
Lost Startup Time	•	•	•	•
Free Flow Speed	•	•	•	•
Headway Factor		•		

(Source: Sadek and Agbolosu-Amison, 2004)

In CORSIM, multiple runs were generated with the use of different random seed numbers, which were automatically developed with a random number generator called CORSEED (Sadek and Agbolosu-Amison, 2004). This utility program was created by the Advanced Traffic Analysis Center (ATAC) at North Dakota State University. A total of 10 simulation runs were generated using 10 different random seed numbers. The results of these simulation runs were then averaged. From the field data, the total travel time was computed as the average of seven probe vehicle runs, which were conducted by driving from one end of the corridor to the other end. The MQL data of 10 cycles was obtained from a portion of signalized intersections in a corridor (Sadek and Agbolosu-Amison, 2004). Calibration parameters were adjusted until simulation results closely modeled field conditions. In the calibration procedure, initial parameters were modified and then used to perform a simulation run. If inadequate results were developed, then the calibration parameters were further adjusted and incorporated into another simulation run. This process continued until field conditions were accurately modeled in the simulation runs.

In the development of weather-specific signal timing plans, saturation flow rate for each weather/road surface condition was coded using reduction factors that were found from the first half of the case study. As for free-flow speeds, they were coded using the reduction factors from the Salt Lake City study conducted by Perrin *et al*. (2001). Table 6-5 presents the reduction factors for saturation flow rate and speed that were used in this study.

Table 6-5 Reduction Factors for Saturation Flow Rate and Free Flow Speed

Weather/Road Surface	Condition % Reduction in Sat.	Flow Rate % Reduction in Free
Dry	0%	0%
Wet	2%	10%
Wet and Snowy	4%	13%
Wet and Slushy	15%	25%
Slushy in Wheel Paths	21%	30%
Snowy and Sticky	16%	35%

(Source: Sadek and Agbolosu-Amison, 2004)

In order to evaluate the benefits of weather-specific signal timing plans properly, the performance of optimal weather-specific plans must be compared to the optimal plan that is created for the "dry" condition. The following procedure was performed to develop weather-specific signal timing plans.

Development of Weather-Specific Signal Timing Plans - Procedure
The first step was to develop optimal plans for the six different weather/road surface conditions, including the "dry" condition. For TRANSYT-7F, the Genetic Algorithm (GA) optimization routine was used to optimize the cycle length, splits, and offsets. The GA was preferred over the traditional hill climbing optimization routine because it allows the model to escape out of local optima. For the GA, the crossover rate was set to 30 percent, and the mutation rate was equal to 1 percent. A population size equal to 20 was used, and the GA was run for 700 generations to make sure a "good" signal plan was obtained. The objective function selected for optimization was the function designed to minimize the Disutility index (DI), which represents a combination of delays and stops. For SYNCHRO, the following optimization steps recommended by the SYNCHRO users' manual were followed: first, the individual intersection cycle lengths were optimized followed by optimization of the splits for each individual intersection. After this, the network wide cycle length was optimized and the network was partitioned into zones. Finally, the signal offsets were optimized using SYNCHRO's quasi-exhaustive search optimization algorithm. For both TRANSYT-7F and SYNCHRO, the optimal plan developed for the "dry" condition was used as a starting point for the search procedure when developing optimal plans for the remaining five weather/road surface conditions.

(Source: Sadek and Agbolosu-Amison, 2004)

To evaluate the likely operational benefits of implementing "special" signal timing plans for each weather and road surface condition, Sadek and Agbolosu-Amison first quantified the traffic conditions from each signal timing plan using the performance measures shown in Table 6-6.

Table 6-6 Performance Measures used for Benefit Assessment

Performance Measures	Traffic Simulation Models			
	TRANSYT-7F	SYNCHRO	CORSIM	SimTraffic
Control/Signal Delay	•	•	•	
Average Delay Time			•	•
Total Travel Time	•	•	•	•
Average Speed	•	•	•	•
Total Stops	•	•		
Fuel Consumption	•	•		

(Source: Sadek and Agbolosu-Amison, 2004)

Then the traffic conditions from the weather/pavement conditions were compared to the traffic conditions from the "dry" base signal timing plan. The percent gain of the performance measures were calculated for each weather condition. This was done first using the macroscopic models, TRANSYT-7F and SYNCHRO. Then the enhanced signal timing plans developed in TRANSYT-7F were analyzed in CORSIM, and the signal timing plans developed in SYNCHRO were analyzed in SimTraffic. This was executed so that a more detailed evaluation of the signal timing plans could be performed. In order to capture the stochastic nature of field conditions, five runs were performed with random seed numbers for each weather/pavement condition in CORSIM and SimTraffic (Sadek and Agbolosu-Amison, 2004). The same random seed numbers were used for all of the inclement weather cases.

Table 6-7 Benefits of Special Timing Plans – CORSIM Results for Dorset Street

Weather Condition	Timing Plans	Control Delay (min/veh)	Avg. Delay Time (min/veh)	Total Travel Time (veh-hrs)	Avg. Speed (mph)
2 – Wet	Under Dry Optimal Plan	0.42	0.71	100.95	23.87
	Weather-Specific Optimal Plan	0.41	0.70	100.66	23.96
3 – Wet and Snowy	Under Dry Optimal Plan	0.42	0.71	104.59	23.02
	Weather-Specific Optimal Plan	0.41	0.70	104.38	23.11
4 – Wet and Slushy	Under Dry Optimal Plan	0.46	0.79	116.54	20.52
	Weather-Specific Optimal Plan	0.44	0.76	116.04	20.65
5 – Slushy in Wheel Paths	Under Dry Optimal Plan	0.47	0.80	123.53	19.22
	Weather-Specific Optimal Plan	0.48	0.80	124.37	19.18
6 – Snowy and Sticky	Under Dry Optimal Plan	0.45	0.78	125.13	18.08
	Weather-Specific Optimal Plan	0.47	0.80	132.78	17.92

(Source: Sadek and Agbolosu-Amison, 2004)

Table 6-8 Benefits of Special Timing Plans – CORSIM Results for Vermont Route 15

Weather Condition	Timing Plans	Control Delay (min/veh)	Avg. Delay Time (min/veh)	Total Travel Time (veh-hrs)	Avg. Speed (mph)
2 – Wet	Under Dry Optimal Plan	0.86	1.23	137.49	21.36
	Weather-Specific Optimal Plan	0.88	1.24	138.55	21.26
3 – Wet and Snowy	Under Dry Optimal Plan	0.88	1.25	141.74	20.60
	Weather-Specific Optimal Plan	0.89	1.27	135.37	20.54
4 – Wet and Slushy	Under Dry Optimal Plan	1.11	1.51	160.87	17.69
	Weather-Specific Optimal Plan	1.05	1.45	159.01	18.03
5 – Slushy in Wheel Paths	Under Dry Optimal Plan	1.21	1.58	168.91	16.47
	Weather-Specific Optimal Plan	1.09	1.50	165.74	16.93
6 – Snowy and Sticky	Under Dry Optimal Plan	1.09	1.52	174.52	15.89
	Weather-Specific Optimal Plan	1.07	1.49	173.29	16.08

(Source: Sadek and Agbolosu-Amison, 2004)

The results from the 10 simulation runs for the microscopic analysis (i.e., 5 runs using CORSIM and 5 runs using SimTraffic) were averaged for each weather condition case. Table 6-7 and Table 6-8 present the percent gain of the CORSIM performance measures (i.e., control delay (min/veh), average delay time (min/veh), total travel time (veh-hrs), and average speed (mph)) for Dorset Street and Vermont Route 15. A simulation time of 15 minutes was used for the microscopic analysis.

As seen, the percent gains for most cases do exist but they appear marginal. Keep in mind that these are the results of microscopic analyses that consist of data for traffic conditions pertaining to individual vehicles. Models of this type of analysis usually require much more detailed data than macroscopic simulation models. Therefore, microscopic simulation model users will gain higher accuracy when modeling field conditions than they would have using macroscopic simulation models.

Sadek and Agbolosu-Amison took the case study to another level by comparing the operational benefits of the signal timing plans for durations of 15 minutes, 1 hour, and 2 hours. Figure 6-9 and Figure 6-10 present the Dorset Street and Vermont Route 15 operational benefits of the signal timing plans for weather/road surface conditions 4 through 6 (i.e., wet and slushy, slushy in wheel paths, and snowy and sticky) for the three duration levels.

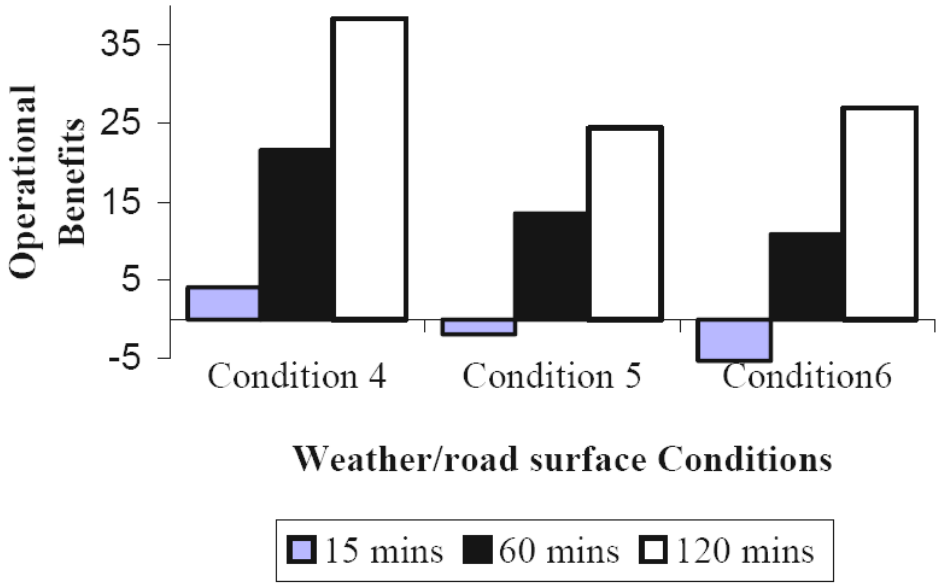


Figure 6-9 Impact of Inclement Weather Duration on Operational Benefits (Dorset Street)
(Source: Sadek and Agbolosu-Amison, 2004)

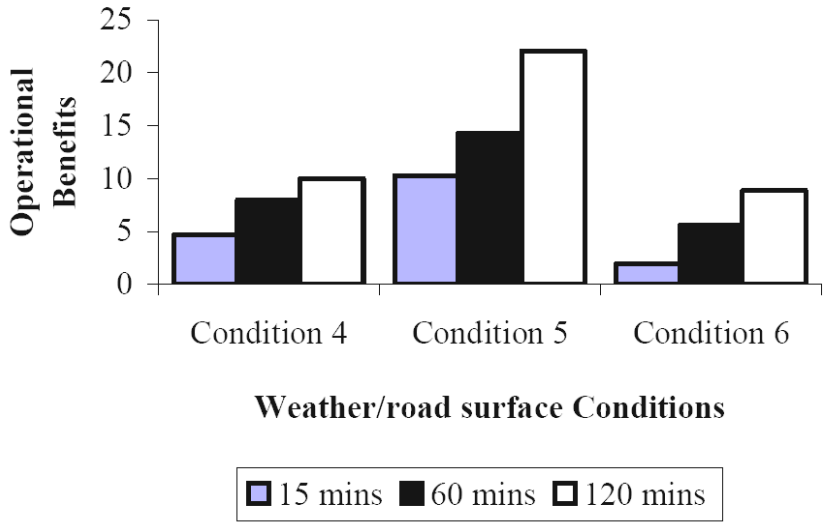


Figure 6-10 Impact of Inclement Weather Duration on Operational Benefits (Route 15)
(Source: Sadek and Agbolosu-Amison, 2004)

Both figures show an increasing trend in operational benefits, which are the percentage gains for control delay (veh/min), as the inclement weather duration increases. For example, the operational benefits on Dorset Street for condition 4 (i.e., wet and slushy) are around 4.1 percent for the 15-minute occurrence, but these operational benefits increase to a whopping 38.4 percent

for the 2-hour occurrence (Sadek and Agbolosu-Amison, 2004). It should be noted that the special signal timing plans on Dorset Street for conditions 5 and 6 (i.e., slushy in wheel paths and snowy and sticky) do not produce any operational benefits for the 15-minute case. Because of this, it can be deemed that the signal timing plans for the Dorset Street intersections will gain better benefits for the 15-minute case if they are operated under normal, dry weather conditions. These figures show that significant operational benefits can occur when the duration of the inclement weather event is longer.

6.2.4. Conclusions and Recommendations

The following presents the conclusions from the results of the case study. These conclusions pertain to the development and implementation of "special" signal timing plans for inclement weather conditions.

Implementing Weather-Specific Signal Timing Plans - Conclusions
▪ The implementation of special signal timing plans for inclement weather resulted in significant operational benefits for both corridors, especially once slushy conditions developed or snow started sticking to the ground; ▪ The operational benefits of inclement weather special timing plans estimated using stochastic, microscopic simulation models tend to be less than those estimated using deterministic, macroscopic models. This is especially true when the time period simulated is short. When the length of the microscopic simulation is increased to one hour, the benefits from microscopic models tend to get closer to those estimated from macroscopic models; and ▪ The duration of the inclement weather event has a significant impact on the benefits realized from inclement weather special timing plans. A significant, consistently increasing trend in operational savings can be observed for increasing durations of the inclement weather event.

(Source: Sadek and Agbolosu-Amison, 2004)

This case study did not take into account the change in traffic demand due to inclement weather conditions. As is known, inclement weather does cause traffic demand volumes to decrease when conditions have reached a severe intensity. For future studies, it is recommended that reductions to traffic demand be quantified and used to develop weather-specific signal timing plans (Sadek and Agbolosu-Amison, 2004).

The operational benefits that were observed from the microscopic model assessment were far fewer than those obtained from the macroscopic models. This is due to the fact that the microscopic models included the stochastic nature of driving conditions. For future research it may be a good idea to make the comparison of benefits that were collected from the stochastic optimization techniques, as utilized in the microscopic simulation models, with the traditional optimization techniques found in macroscopic simulation models such as TRANSYT-7F and SYNCHRO (Sadek and Agbolosu-Amison, 2004).

6.2.5. Guidance

Those who are interested in performing their own analysis to observe the operational benefits of implementing weather-specific signal timing plans may incorporate the steps that were taken in this case study. An agency can collect traffic data during inclement weather conditions, which can be directly input into macroscopic models, such as TRANSYT-7F and SYNCHRO, which have the capabilities to develop optimal signal timing plans. In order to capture the random

nature of driving conditions, microscopic models should be used to evaluate the operational benefits of weather-specific signal timing plans.

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