Validating Traffic Simulation Models to Inclement Weather Travel Conditions with Applications to Arterial Coordinated Signal Systems

Dr. Adel W. Sadek, PI
Seli J. Amison-Agbolosu, Graduate Research Assistant

Prepared For
The New England Transportation Consortium
November 2004

NETCR47

Project No. 02-7

This report, prepared in cooperation with the New England Transportation Consortium, does not constitute a standard, specification, or regulation. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the views of the New England Transportation Consortium or the Federal Highway Administration.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NETCR 47	N/A	N/A

4. Title and Subtitle	5. Report Date
Validating Traffic Simulation Models to Inclement Weather Conditions with Applications to Arterial Coordinated Signal Systems	November 2004
	6. Performing Organization Code: N/A
7. Author(s): Adel W. Sadek and Seli J. Amison-Agbolosu	8. Performing Organization Report No.: NETCR 47
9. Performing Organization Name and Address: University of Vermont, Burlington, VT 05405	10 Work Unit No. (TRAIS): N/A
	11. Contract or Grant No.: N/A
12. Sponsoring Agency Name and Address: New England Transportation Consortium, 179 Middle Turnpike, University of Connecticut, U-5202, Storrs, CT 06269-5202	13. Type of Report and Period Covered: Final
	14. Sponsoring Agency Code: NETC 02-7 A study conducted in cooperation with the U.S. DOT

15 Supplementary Notes

N/A

16. Abstract

Congestion along arterial systems in New England is often the result of adverse weather conditions, which typically change the normal traffic flow parameters and render the normal signal plans unsuitable. With recent advances in communications and signals' hardware, there is a need to explore the feasibility and benefits of implementing signal-timing plans, specifically tailored for inclement weather conditions. The current study has two main objectives: (1) to assess the impact of inclement weather on traffic flow parameters at signalized intersections in northern New England; and (2) to evaluate the likely operational benefits of implementing weather-specific timing plans. To assess inclement weather impact, traffic flow under normal and inclement weather conditions at a signalized intersection were carefully observed over two winter seasons. The weather/road surface conditions were categorized into six different classes, and values for the saturation headways and startup lost times were collected for each weather condition. Statistical analyses reveal that inclement weather does have a significant impact on the values of saturation headways, particularly once slushy conditions start developing or once snow start sticking to the ground. Startup lost time, on the other hand, does not appear to be as significantly impacted. To assess the likely benefits of weather-specific plans, four signalized arterial corridors were selected as case studies, two from the State of Vermont and another two from the State of Connecticut. Optimal signal plans were developed for these corridors for the six different weather/road surface conditions using both TRANSYT-7F and SYNCHRO models. The likely benefits of the "special" timing plans were then determined using the macroscopic models of TRANSYT-7F and SYNCHRO models first, and then using the more detailed microscopic simulation environment of CORSIM and SIMTRAFFIC models. Results from the study indicate that operational benefits are to be expected from implementing weather-specific timing plans, and that the benefits estimated from the use of macroscopic, deterministic models tend to be higher than those determined by stochastic, microscopic models.

17. Key Words	18. Distribution Statement
	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	67	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

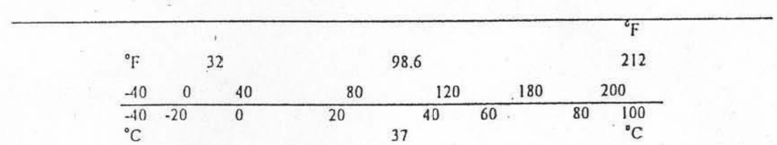


TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NETC 02-7: Validating Traffic Simulation Models to Inclement Weather Travel Conditions with Applications to Arterial Coordinated Signal Systems

CHAPTER 1 - INTRODUCTION

1.1 Problem Statement

Gridlock along arterial systems in New England is often the result of adverse weather conditions. Snow and icy conditions resulting from inclement weather typically result in lower speeds, longer startup lost times, and abnormal driver behavior. These in turn render the normal signal coordination plans unsuitable, because the traffic flow parameters that were used to develop the "normal weather" plans have changed. In the ideal situation, a traffic control signal should *adapt* to changes in the travel environment, and efforts are currently under way to develop such real-time adaptive traffic control systems. Examples of these systems include: (1) the Split Cycle Offset Optimization Technique (SCOOTS) developed in England (Bretherton, 1996); (2) the Sydney Coordinated Adaptive Traffic System (SCATS) developed in Australia (Venglar and Urbanik, 1995); and (3) the Regional Hierarchical Optimized Distributed Effective System (RHODES) developed in the US (Head *et al.*, 1992).

Despite their contribution to improving travel conditions, adaptive controllers have their own problems. They are costly to deploy and maintain, and therefore not all jurisdictions can afford their usage. It is generally accepted that we are still some years away from the widespread adoption of these systems. As a compromise between an automatically adaptive system (*real-time adaptive controller*) and a system that does nothing to react to changes in traffic flow conditions (*traditional system controller*) during inclement weather, lies the idea of devising special timing plans, specifically tailored to accommodate inclement weather traffic flow.

In the past, the implementation of special plans for inclement weather conditions was quite impractical, because this would have required a traffic operator to manually change the settings of each traffic controller in the field. The recent advances in traffic signal controllers and communications systems, however, have made the implementation of "special" signal timing plans more practical. It is now quite possible for a traffic operator to remotely access and change controllers settings, via communications links between the field controllers and a central location (a traffic control center for example). Given this, there is currently a need for exploring the feasibility and likely benefits of implementing signal timing plans, specifically tailored to accommodate traffic flow during inclement weather. The current study was initiated in response to this need.

1.2 Goals and Objectives

The objective of the current study is twofold. The first objective is to explore how to best calibrate simulation models to inclement weather conditions in New England. This is accomplished by first determining the changes in the different traffic flow parameters resulting from inclement weather, and then adjusting the simulation models' parameters to get their results closer to reality. With the simulation models calibrated, the second objective of the study is to use the calibrated model to investigate the feasibility and benefits of tailoring signal timing plans to inclement weather conditions along Northern New England arterials. Specifically, therefore, the project has the following objectives:

(1) To determine the impacts of inclement weather (i.e. snow and ice) on discharge headways and startup lost times at signalized intersections;
(2) To calibrate various traffic simulation models to inclement weather travel conditions;
(3) To use the calibrated simulation model to assess the feasibility and operational benefits of implementing special timing plans specifically tailored for inclement weather conditions.

1.3 Rationale

Most of the timing plans developed and used by field controllers have worked effectively to reduce the congestion problems at signalized intersections during off peak periods but sometimes tend to fail during peak periods, when the demand exceeds the intersection capacity. As a result, commuters experience longer delays than normal. When inclement weather conditions occur, a condition that results in a negative effect on driver behavior and traffic flow parameters, the congestion problems compound resulting in more delays, longer start up times and reduced speeds. Intuitively we can argue that the abnormal behaviors of drivers during inclement weather affect the speeds, startup times and result in wider gaps between adjacent moving vehicles in a traffic stream. Unlike normal weather (*Dry* weather), during inclement weather (say severe rain and snow), there is a potential for less traction between the wheels and the pavement surface and also the visibility on the roadway ahead of the driver is reduced. These factors directly affect traffic flow parameters.

Recent studies from different parts of the United States have confirmed this assertion that inclement weather does have an impact on traffic flow parameters (Maki, 1999; Perrin *et al*., 2001). The effect of inclement on the flow parameters will make the current signal timing plans inappropriate because they were developed using a different set of flow parameters. Thus knowing the extent of impact of inclement weather on the traffic flow parameters, we can obtain more representative values for these flow parameters for inclement weather and design special timing plans that can be used when inclement weather conditions occur.

None of the studies done on the effect of inclement weather on traffic flow parameters across the United States included New England. As a result there is an urgent need to investigate the impact of inclement weather on New England traffic flow parameters. As mentioned above, this constitutes the current study's first objective. With this knowledge, transportation professionals can then use these new traffic flow parameters that result from inclement weather to develop a library of special plans for the different inclement conditions that can develop. Before doing that, however, there is a need to investigate the feasibility and benefits of implementing these plans; hence, the study's second objective.

1.4 Scope

This study investigates the feasibility and benefits of implementing a library of inclement weather special signal timing plans for New England. Data for quantifying the impact of inclement weather on traffic flow parameters are collected for two winter seasons (2002/2003 and 2003/2004) in order to validate the results. For assessing the likely benefits of the special timing plans, four arterial corridors, two from the state of Vermont and another two from the state of Connecticut, are selected as case studies. The likely benefits are assessed using both macroscopic traffic simulation models, namely TRANSYT-7F (Transportation Research Center, 1998) and SYNCHRO (Trafficware Corporation, 2001), as well as the more detailed microscopic models, CORSIM (ITT Systems & Sciences Corporation, 1998) and SimTraffic (Trafficware Corporation, 2001).

1.5 Organization of the Report

The current report is organized as follows:

Chapter 1 introduces the research problem considered in this study, and outlines the study's objectives, rationale and scope.

Chapter 2 provides a detailed literature review focusing on prior research in assessing the impact of inclement weather on traffic flow and the feasibility of implementing special timing plans for inclement weather. The traffic analytical tools needed in order to conduct this study are also reviewed.

Chapter 3 presents the results from the current study's field data collection effort aimed at evaluating the impact of inclement weather on traffic flow parameters at signalized intersections. The chapter also compares our results to the previous published results.

Chapter 4 describes the methodology used to evaluate the likely benefits of implementing special plans for inclement weather conditions. The chapter also presents and discusses the results obtained regarding inclement weather special timing plans' operational benefits.

Finally, *chapter 5* summarizes the main conclusions derived from the study and provides some recommendations for future research.

CHAPTER 2 - LITERATURE REVIEW

To design "*special*" signal timing plans for inclement weather and to assess the feasibility of this approach for Northern New England, traffic engineers need to undertake these three steps:

1. Gain a better understanding of the impacts of inclement weather on traffic flow parameters;
2. Develop analytical tools that can accurately model traffic flow during inclement weather;
3. Understand how to calibrate and validate these tools to inclement weather conditions.

As a first step in this study, a detailed literature review focused on each of the above three topics was conducted. Results from this literature review are briefly discussed below.

2.1 Impact of Inclement Weather on Traffic Flow Parameters

The fact that inclement weather does have an impact on traffic flow parameters is quite intuitive [Perrin *et al*, 2001]. Most individuals living in cold climatic regions recognize that their commute time is likely to become longer on snowy days. While the negative impact of inclement on traffic flow conditions is widely acknowledged, there has been limited research that tried to precisely quantify the impacts of inclement weather on traffic flow parameters. In addition, most of this research has focused on freeway traffic with little attention paid to traffic flow on signalized arterials.

2.1.1 Freeways

For *freeways* the studies conducted so far and relevant to this study are as below:

Hanbali (1994) in a study to determine the economic impacts of winter road maintenance on road users, used results from a Federal Highway Administration (FHWA) study that found an average speed reduction of 13 to 22% on freeways during adverse weather. Ibrahim and Hall (1994) conducted a study to find the effect of adverse weather conditions on freeway operations. The traffic data used was from a freeway traffic management system for the Queens Elizabeth Way in Mississauga, Ontario. Among the variables recorded, speed was the most prevalent for this study. They found site–specific reductions in free flow speeds in the order of 1.9 mph for light snow, in the range of 3.1 to 6.2 mph for heavy rain, and in the range of 23.6 to 31 mph during heavy snow.

Wallman *et al*. (1997) conducted a study in Sweden where continuous measurements of traffic (including vehicle speed and flow) and weather variables were undertaken at five road sites in central Sweden during the winter of 1998-1999, along with visual observations of the state of the roads were made at the same time. Weather data collected were precipitation types (rain or snow), and risks of slipperiness were gathered from Road Weather Information Systems stations

of the Swedish National Road Administration close to the observation sites. Wallman et al found reductions in average speed during ice and snowy conditions in the range of 10 to 30%.
The FHWA (1997) in their study to investigate the economic impacts of adverse weather on all highway types measured the free flow speeds of vehicles at varying intensity of inclement weather. Their findings showed that, there is a direct relationship between increasing severity in road weather conditions and percentage speed reductions. They observed percentage speed reductions in the range of 13% to 42% for seven different road weather conditions classified from a previous study; dry (0% reduction), wet (0% reduction), wet and snowy (13% reduction), wet and slushy (22% reduction), slushy in wheel paths (30% reduction), snowy and sticky (35% reduction) and snowy and packed (42% reduction) conditions.

Liang *et al*. (1998) conducted a case study in Idaho to find the effects of visibility and other environmental factors on driver speed. The project area was in Idaho and included an arterial corridor of I-84 in southeast Idaho and Northwest Utah. The results showed that average speed reductions were in the order of 11.9 mph during snow events, and that the overall variability in average speed during snow events was nearly three times larger than normal weather conditions.

Finally, Knapp and Smithson (2001) used mobile video data collection equipment to evaluate the impacts of adverse weather on average speed during seven winter events at a particular interstate location in Iowa. Winter weather data was collected and summarized by 15-min time periods. The data collected included traffic volumes, vehicle speeds, vehicle gaps or headways, visibility, and roadway snow cover. Their study showed that visibility below 0.4 km (0.25 mi) and snow cover on the roadway lanes could reduce average off-peak winter weather vehicle speeds by approximately 6.3 and 11.7 km/h (3.9 and 7.3 mph) respectively.

2.1.2 Signalized Intersections

For signalized intersections, a limited number of research studies have focused on assessing how inclement weather affects saturation flows, capacities, average speed and startup lost time. The studies conducted so far are as below:

In the United Kingdom, Gilliam and Withall (1992) showed that for wet pavements delay increased by 11%, and saturation flow rates reduced by 6%. In Anchorage Alaska, Bernardin Lochmueller and Associates, Inc. (1995), assessed the changes in speeds and the saturation flows during severe weather conditions on a network consisting of 24 signals. Several traffic flow parameters (including saturation flow, speed, and startup lost times) were measured during normal summer condition, normal winter conditions, and during severe winter weather conditions. Bernardin Lochmueller and Associates, Inc. found that the signal timing plans developed using summer weather conditions were not suitable for inclement weather conditions. They conclude that developing “special” timing plans for inclement weather could reduce travel time by 13% and average delay by 23%.

Maki (1999), in a study for the Minnesota Department of Transportation (MnDOT), evaluated the feasibility of implementing timing plans for inclement weather. During the study, extensive data was collected during normal weather PM peak periods and during adverse weather PM peak periods. The data collected includes, signal timing plans, geometrics, turning movements counts, travel time runs, volume and occupancy, startup delay and saturation flow rate for a snow storm with three or more inches of snow. All the data was collected during the winter season of 1998-1999. The study concludes with the following findings; the average speed reduced from 44mph during normal weather conditions to 26mph during adverse weather conditions, the saturation flow rate reduced from 1800 vehicles per lane per hour (vplph) to 1600vplph, and startup delay increased from 2 to 3 seconds. Maki concludes that inclement weather timing plans could reduce average vehicle delay by 13%.

Perrin *et al*. (2001) quantified the impacts of inclement weather on traffic flow parameters in Salt Lake, Utah. They recorded the values of a number of traffic flow parameters during dry weather and various intensity levels of rain and snow. In all, seven inclement weather severity conditions at two signalized intersections during the period of 1999-2000 were considered. Their study showed an average decrease in saturation flows of 20%, a decrease in average speed of 30%, and an increase in startup lost time of 23%. Perrin et al also found that the largest decrease in vehicle performance occurs when snow and slush begins to accumulate on the road surface.

Finally, Padget *et al*. (2001), investigated whether drivers of SUVs, pickup trucks, and passenger cars choose different vehicle speeds during winter weather. The study took place on an urban arterial street in Ames, Iowa, between November 1999 and April 2000. Vehicle speed, roadway condition, time of day, and vehicle type were recorded during normal and five different winter-weather pavement surface conditions. The results indicated that winter-weather vehicle speeds for all three-vehicle types were significantly less than their normal weather speeds and that during the day a large percentage of the speed reduction occurs after snow began to accumulate in the gutter pans of the roadway. They also found that, speed variability between vehicles types increased during different winter-weather conditions. The study also showed that the magnitude of the speed differences between SUV, pickup trucks, and passenger cars increased with roadway snow cover, but was always less than 5.6 km/h (3.5 mph).

As can be seen from the literature review above, while there have been a limited number of studies that have attempted to quantify the impacts of adverse weather on traffic flow parameters, none of these studies have focused on New England conditions. These studies, however, clearly show that adverse weather can have a significant impact on traffic flow parameters, and that this significant impact needs to be accounted for in the various traffic flow analyses.

2.2 Analytical Tools for Modeling Traffic Flow

To design *special* signal timing plans for inclement weather conditions in Northern New England as well as to evaluate the feasibility and benefits of this approach, traffic engineers are in need of analytical tools capable of accurately modeling traffic flow under inclement weather. Traffic simulation models are among the most useful analytical tools available to traffic engineers for conducting traffic-engineering studies. The basic idea behind the use of such models is to build a computer model that mimics the real-world conditions. Once the model is developed, a traffic engineer could then experiment with different control strategies and design configurations and determine their impacts on the system. Simulation models thus offer several advantages over field experiments. Some of the advantages are:

1. They are less costly than field experiments.
2. Faster results are obtained field experiments.
3. Traffic simulation models avoid the disruption of traffic operations that characterizes field experiments.

Traffic simulation models also form the basis of traffic signal optimization programs such as TRANSYT-7F (Transportation Research Center, 1998) and SYNCHRO (Trafficware Corporation, 2001).

Given the aforementioned advantages of simulation, simulation thus appears to be the right tool for use in determining whether it would be beneficial to develop signal timing plans for adverse weather conditions. In general, traffic simulation models could be divided into two groups: microscopic models and macroscopic models. Microscopic traffic models track the position of individual vehicles in time and space using car-following logic (gaps between moving vehicles). Examples of microscopic models include CORSIM (ITT Systems & Sciences Corporation, 1998) and SimTraffic (Trafficware Corporation, 2001). Macroscopic models, on the other hand, consider the characteristics of the traffic stream as a whole and are based on macroscopic relations that relate traffic flow to density and speed. Examples of macroscopic models include the models used within the traffic signal optimization software, TRANSYT-7F and SYNCHRO.

Most of the traffic research studies that used simulation models, however, were based on normal weather conditions. For inclement weather conditions signal timings, little research work has been done using these simulation-modeling tools. Bernardin Lochmueller and Associates, Inc. (1995) in their study used TRANSYT-7F to develop signal timing plans for Anchorage Alaska. Maki (1999) in the study on adverse weather signal timing for Minnesota DOT used SYNCHRO III to develop signal-timing plans for adverse weather. Finally, Perrin et al [2001] used CORSIM and SYNCHRO to simulate an arterial corridor using adverse weather traffic flow parameters.

The use traffic simulation models for inclement weather studies can be seen as an evolving area of research among the transportation research community. For normal weather studies, extensive research studies have provided much information on what traffic flow parameters to adjust but this is not the case for inclement weather conditions. Unfortunately, with inclement weather the number of studies contributing to the literature is not adequate to enhance the knowledge and confidence in the usage of these models. Furthermore, to be able to use any of these traffic tools for any traffic studies, it is imperative that one understands how to calibrate these models.

2.3 Calibrating Traffic Simulation Models

Before simulation models can be used to analyze a given traffic scenario, however, the model needs to be calibrated and validated in order to guarantee that the model is an accurate approximation of reality. Calibration typically involves adjusting the model's parameters, such as the car following sensitivity factor (for microscopic models), the speed density relationship (for macroscopic models), the discharge headways and startup lost time at the intersections, in order to get the model results to agree with real-world observations. Validation simply means comparing the field performance measures of average queue/ maximum queue, average vehicle delays and travel time with the models output. A model can be regarded as an accurate mimicking of the real world conditions if the field performance measures agree with those given by the model outputs. Since inclement weather results in a change in one or more of the model parameters, there is a genuine need for a study on how to best calibrate, simulation models to mimic inclement weather travel conditions.

The literature review below gives an insight into what researchers recommend as procedures that can be followed in calibrating traffic simulation models. For this project, our focus is on arterial corridors, thus recommended calibration steps related to arterial corridors will be of much importance to us for this portion of the literature review.

Milam *et al*. (2002), in their study presented an initial set of recommended guidelines for the development and application of traffic simulation models. The guidelines they gave are based on previously published information, interviews with practitioners, and results from successfully completed simulation projects. According to Milam et al, there is a need for guidance on how to use these simulation models, because the lack of guidance or direction has lead to conflicts between models users, inappropriate use of the models, and inaccurate results from the models. Milam et al defined calibration as the process by which the individual components of simulation model are adjusted or tuned so that the model will accurately represent field measured traffic conditions. The table below lists the traffic flow parameters recommended for calibration for the CORSIM model. In this table, driver type refers to how aggressive drivers are.

Table 1. Traffic Flow Parameters Recommended for Calibration

Parameters	Effects	Default	Calibration Range
Startup Lost Time	Link specific	2.0 seconds	0.5 – 9.9 seconds
Queue Discharge Rate	Link specific	1.8 seconds (2000vphpl)	1.4 – 2.4 seconds (1500 – 2270) vphpl
Acceptable gap in oncoming traffic for permissive left-turners	Network Wide	Driver type 1 (7.8 Seconds) to Driver type 10 (2.7 Seconds)	2.7 to 7.8 Seconds for Driver types 1 to 10
Acceptable gap in oncoming traffic for right turners on red or right turn at the stop sign	Network Wide	Driver type 1 (10.0 Seconds) to Driver type 10 (3.6 Seconds)	3.6 to 10.0 Seconds for Driver types 1 to 10

For validation, the recommended traffic flow characteristics are as listed in the table below.

Table 2. Traffic Flow Characteristics Recommended for Validation

Parameters	Description	Validation Criteria
Volume Served	Percentage difference between input volume and *CORSIM* output or assigned volume	95 to 105% of observed value
Average Travel Time	Standard deviation between floating car average travel time and *CORSIM* simulated average travel time for a series of links	1 standard deviation
Average Travel Speed	Standard deviation between floating car average travel speed and *CORSIM* simulated average travel speed for individual links	1 standard deviation
Average and Maximum vehicle Queue Length	Percentage difference between observed queue lengths and *CORSIM* simulated queue lengths	80 to 120% of observed value

Milam et al.'s paper addressed the fact that any analysis of *CORSIM* output requires that more than one simulation run be performed and that average results be used. They also recommend that variation in the results be calculated and reported, and emphasize that this is needed because *CORSIM* and other microscopic traffic simulation programs are based on stochastic algorithms (that is random processes) that describe driver behavior and traffic operations.

Merritt (2004) proposed a methodology for the calibration and validation of the stochastic microscopic traffic simulation model *CORSIM*, by focusing on Swedish road traffic conditions, using empirical data from a section of the arterial road in the city of Uppsala, Sweden. In this study, data from two traffic scenarios were collected during the AM peak and midday peak. The midday peaks were used for calibration while the AM peaks were used for validation. Merritt suggested that though *CORSIM* has a large number of default values, hence enabling user inputs to be kept to a minimum, these default values may not always be a good representation of the traffic situation under study. One way to overcome this shortcoming is to designate and define a test site where models are implemented, calibrated, and evaluated using empirical data.

The parameters Merritt chose for calibration were the statistical means of free flow speeds, start-up lost times, queue discharge headway and accepted gaps. Comparing the model's output to field data was based on the following measures of effectiveness (MOEs): (1) percentage stopped, (2) maximum queue lengths (in vehicles), (3) delay time (secs/veh) and (4) total queue time (veh–min). Merritt also recommended that a robust statistical analysis be conducted for each of these parameters to help capture the randomness involved in a traffic stream. In that study, confidence interval and goodness of fit tests where performed to detect the amount of variation in the results and were also used determine the number of replications needed to ensure reliable predictions.

Cohen [2004] introduced an approach for calibration and validation of traffic simulation models. According to Cohen, understanding the meaning of calibration and validation and what parameters to use in either case is a necessary step for understanding how to calibrate and validate traffic simulation models for a particular case study. Cohen defined calibration *as* the adjustment of parameters in a model so as to represent local conditions, and validation as a comparison of measures of effectiveness as computed by a model and as observed in field data under the same traffic conditions. Cohen stressed on the fact that validation can only be attempted after the model has been effectively calibrated. In his study, the calibration parameters chosen were queue discharge headway, startup delay and free flow speed.

Dowling and Skabardonis [2004] provided a systematic framework for calibration of microscopic simulation models that is not model specific. According to Dowling and Skabardonis, calibration is necessary because no single model can be expected to be equally accurate for all possible local traffic conditions and behaviors, and therefore every model must be adapted to local conditions. They recommended a three-step strategy for calibration; capacity calibration, route choice calibration and system performance calibration. They suggested that to satisfy these steps, the following data needed to be collected: traffic counts and measures of systems performance such as travel times, speeds, delays and queues. Also for validation, parameters used as measures of system performance must be collected simultaneously with the traffic counts.

As can be seen from the literature review, calibration is a necessary condition for any engineering study involving the use of traffic simulation models. Thus to be able to develop special signal timing plans for inclement weather conditions, the models have to be well calibrated to replicate the inclement weather travel conditions. To author's best knowledge, there has not been any guidelines as to calibrating these models to inclement weather conditions.

To calibrate traffic simulation models for inclement weather, data collection could be a major problem as with calibrating traffic simulation models to normal weather. This could be very expensive and as a result not all the parameters needed to successfully calibrate the model for each road weather condition can be successfully obtained. As a way of solving this problem, a well-calibrated model for the dry condition can be used as a base model to help calibrate the inclement weather travel conditions. This was the procedure followed in the current study.

CHAPTER 3 – INCLEMENT WEATHER IMPACT ON TRAFFIC FLOW AT SIGNALIZZED INTERSECTIONS

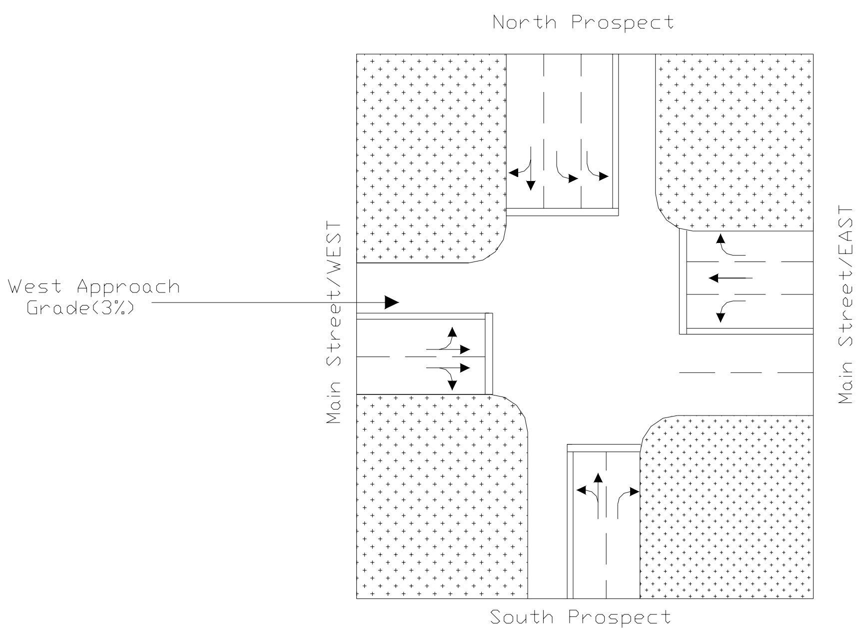
The focus of this chapter is on describing the field data collection effort conducted in order to quantify the impact of inclement weather on traffic flow parameters, specifically discharge headways and startup lost times, at signalized intersections. The chapter is divided into the following sections. Section one describes how the data was collected and reduced. The statistical analyses performed on the data and the results and insights derived are presented and discussed in section two. Section three compares the results from this study to results from previous studies that were conducted in other parts of the United States. Finally, the main conclusions derived from the study are summarized in section four.

3.1 Data Collection and Reduction

3.1.1 Study Site

A study site located in the City of Burlington, Vermont was selected for assessing the impact of inclement weather on traffic flow parameters. The chosen site was the intersection of Main Street, a collector that runs through the University of Vermont, and South Prospect (Figure 1).

Figure 1. Main Street/South Prospect Intersection



The Main Street/South Prospect intersection was chosen for three prime reasons:

1. Heavy traffic volumes during all peak periods;
2. Proximity to the University of Vermont, which facilitated the data collection process, especially during inclement weather; and
3. The differences in grades between the East Bound (EB: grade=3%) and West Bound (WB: grade=0%) directions, which would allow for assessing the impact of the grade of the approach on inclement weather traffic flow parameters.

Traffic flow data were collected at the intersection using a Digital Video Camera Recorder, and the weather/road surface condition was determined from visual observation. In recording the weather/road surface condition, the study used the classification scheme specified by the FHWA (FHWA, 1997), which classifies the road condition into one of the following six classes: (1) dry; (2) wet; (3) wet and snowy; (4) wet and slushy; (5) slushy in wheel paths; and (6) snowy and sticky. The data were collected between the hours of 7:00 a.m. and 7:00 p.m., and was not restricted to the peak periods due to the unpredictable nature of snowfall intensity.

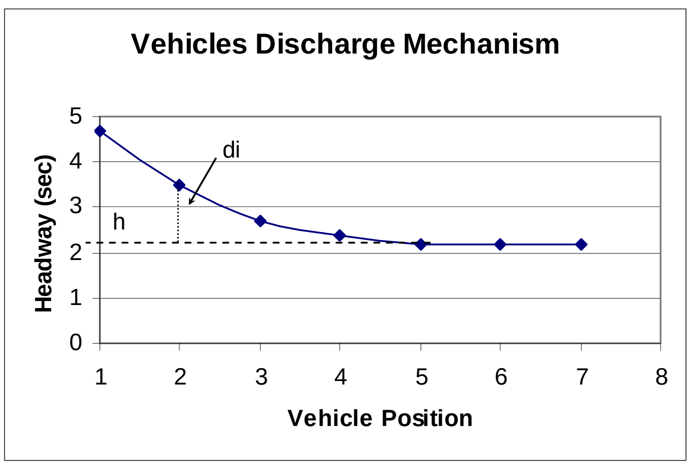
3.1.2. Traffic Parameters

The parameters of prime interest to this study were the startup lost times and saturation or discharge headways. These two parameters were directly extracted from the data collected. A brief description of each of these two parameters is given below (McShane et al., 2004).

3.1.2.1 Saturation Headway

Observations of the way vehicles discharge from a queue have revealed that if the recorded discharge headways (i.e. the interval between the time one vehicle crosses the stop bar and the time the following vehicle crosses) are plotted against the vehicle position in the queue, a graph similar to Figure 2 is obtained.

Figure 2. Discharge Headways at Signalized Intersections



As can be seen, the first few headway are relatively long, then after the fourth or fifth vehicle, the discharge headways typically level out towards a constant value. This value is known as the *saturation headway (h)*, and represents the average headway that can be achieved by a saturated, stable moving queue or vehicles, or the maximum rate at which vehicles can depart from a stop bar, provided that there are vehicles waiting in the queue. Once the saturation headway is determined, the saturation flow rate, *s*, which gives the maximum rate of traffic flow per lane at a signalized intersection assuming that the lane gets 100 percent green time, can be easily computed as the inverse of the saturation headway multiplied by 3600.

3.1.2.2. Startup Lost Time

As Figure 2 shows, for the first four or five vehicles, the headway is actually greater than the saturation headway, *h*, since the drivers of those first four or five vehicles typically require more reaction time in order to accelerate. The sum of the differences between the actual headway for those first vehicles and the saturation headway (d_i in Figure 2) is referred to as the startup lost time, l_1. This l_1 represents the time lost at the beginning of each phase as a result of the additional reaction time required by the first four or five vehicles in a queue.

3.1.3. Data Collection and Reduction

Table 3 gives a summary of the data collected for both 2002/2003 and 2003/2004 winter seasons. For 2002/2003, at least 30 hours of videotaped data were collected over a 3-month period, which corresponded to data from a total of 446 signal cycles. For the 2003/2004 winter season, the snowfall was more intense and frequent than the 2002/2003 season. As a result, more data were collected as compared to the previous year, which resulted in at least 48 hours of videotaped data over a 4-month period, corresponding to data from a total of 510 signal cycles.

Table 3. Number of Signal Cycles Collected for Each Weather/Road Surface Condition

Inclement Weather Condition	**Number of Signal Cycles**	
1. Dry	**2002/2003 Season**	**2003/2004 Season**
2. Wet	82	85
3. Wet and Snowy	110	83
4. Wet and Slushy	100	111
5. Slushy in Wheel Paths	68	98
6. Snowy and Sticky	38	64
TOTAL	**446**	**510**

From the traffic flow data collected, the saturation headways and the startup lost times were extracted from the videotapes for the six-weather/road surface conditions. The stop line on a specific approach was chosen as a reference point, and with the help of a stopwatch, the startup lost times and the saturation headways were extracted for only traffic conditions that had at least 5 vehicles in a standing queue, before they get the green signal. The data was extracted for only one lane per approach for both the EB and WB directions.

For the 2002/2003 winter season, the number of data points obtained for the WB direction was more than that obtained for the EB direction. In addition, with the exception of the *Slushy in Wheel Paths* condition (condition 5) for the EB direction, data were successfully collected for all the road surface conditions during the 2002/2003 winter. For condition 5, the length of the queue on the EB direction was too short to allow for accurately estimating the saturation headway or the startup lost time. For 2003/2004 winter season, enough data were successfully obtained for both the EB and WB approaches for the six weather/road surface conditions.

3.2 Statistical Analysis and Results

To understand the impact of inclement weather on traffic flow parameters (i.e. saturation headways and startup lost times), a robust statistical analysis was performed for both 2002/2003 and 2003/2004 winter seasons. The statistical tools used included both *descriptive* and *inferential* statistics. The analysis was performed separately first on each data set (i.e. each winter season), and the results obtained from each season were then compared in order to validate the conclusions made. Thus, the 2002-2003 data was used to evaluate the impact of inclement weather, and the 2003-2004 data was used for validating the 2002-2003 results.

3.2.1. Descriptive Statistical Analysis

To describe the basic features of both the saturation headways and the startup lost times for both winter seasons, Minitab (Minitab, Inc., 2000) descriptive statistical outputs and comparative box plots were used. Tables 4 and 5 show the mean, trimmed mean and the median values for the 2002/2003 and 2003/2004 data sets, respectively.

Table 4. Descriptive Statistics for 2002/2003 Saturation Headway & Startup Lost Time

SATURATION HEADWAY

Descriptive Statistics: For EB and WB Road Surface Conditions

Variable	N	Mean	Median	TrMean	StDev	SE Mean
Dry/EB	189	2.2397	2.2200	2.2301	0.2332	0.0170
Dry/WB	175	2.0388	1.9630	2.0249	0.2529	0.0191
Wet/EB	139	2.3100	2.2700	2.3020	0.3112	0.0264
Wet/WB	282	2.0761	2.0540	2.0723	0.1714	0.0102
Wet&Snowy/EB	59	2.4153	2.4170	2.4017	0.3816	0.0497
Wet&Snowy/WB	187	2.1287	2.0600	2.1217	0.2763	0.0202
Wet&Slushy/EB	54	2.4144	2.4150	2.3919	0.4313	0.0587
Wet&Slushy/WB	136	2.3917	2.3750	2.3881	0.4013	0.0344
Slushy/WB	101	2.5794	2.6760	2.5859	0.3113	0.0310
Snowy&Sticky/EB	36	2.6714	2.6440	2.6628	0.2992	0.0499
Snowy&Sticky/WB	95	2.4407	2.4580	2.4391	0.2334	0.0239

STARTUP LOST TIME

Descriptive Statistics: For EB and WB Road Surface Conditions

Variable	N	Mean	Median	TrMean	StDev	SE Mean
Dry/EB	45	2.203	2.125	2.176	1.179	0.176
Dry/WB	35	1.839	1.905	1.828	1.005	0.170
Wet/EB	56	2.421	2.345	2.358	1.409	0.188
Wet/WB	64	1.980	1.751	1.942	1.125	0.141
Wet&Snowy/EB	32	2.177	1.916	2.079	1.653	0.292
Wet&Snowy/WB	72	2.280	2.430	2.276	1.131	0.133
Wet&Slushy/EB	32	1.293	0.960	1.185	1.323	0.234
Wet&Slushy/WB	51	2.000	1.894	1.943	1.293	0.181
Slushy/WB	41	1.901	1.939	1.841	1.329	0.208
Snowy&Sticky/EB	13	3.042	2.832	2.865	1.764	0.489
Snowy&Sticky/WB	36	2.199	2.093	2.166	1.449	0.242

Table 5. Descriptive Statistics for 2003/2004 Saturation Headway & Startup Lost Time

SATURATION HEADWAYS

Descriptive Statistics: For EB and WB Road Surface Conditions

Variable	N	Mean	Median	TrMean	StDev	SE Mean
Dry/WB	265	2.0824	2.0640	2.0750	0.1789	0.0110
Dry/EB	153	2.2236	2.1880	2.2259	0.2960	0.0239
Wet/WB	155	2.1419	2.1780	2.1439	0.1576	0.0127
Wet/EB	206	2.2672	2.2530	2.2612	0.2079	0.0145
Wet&Snowy/WB	269	2.2623	2.2440	2.2613	0.2027	0.0124
Wet&Snowy/EB	152	2.3322	2.3180	2.3232	0.2106	0.0171
Wet&Slushy/WB	325	2.3621	2.3580	2.3574	0.2063	0.0114
Wet&Slushy/EB	108	2.4643	2.4770	2.4535	0.3144	0.0303
Slushy/WB	179	2.4098	2.3770	2.4122	0.2651	0.0198
Slushy/EB	80	2.6906	2.6925	2.6840	0.2904	0.0325
Snowy&Sticky/WB	134	2.4823	2.4600	2.4835	0.2703	0.0233
Snowy&Sticky/EB	51	2.7547	2.7000	2.7576	0.4352	0.0609

STARTUP LOST TIME

Descriptive Statistics: For EB and WB Road Surface Conditions

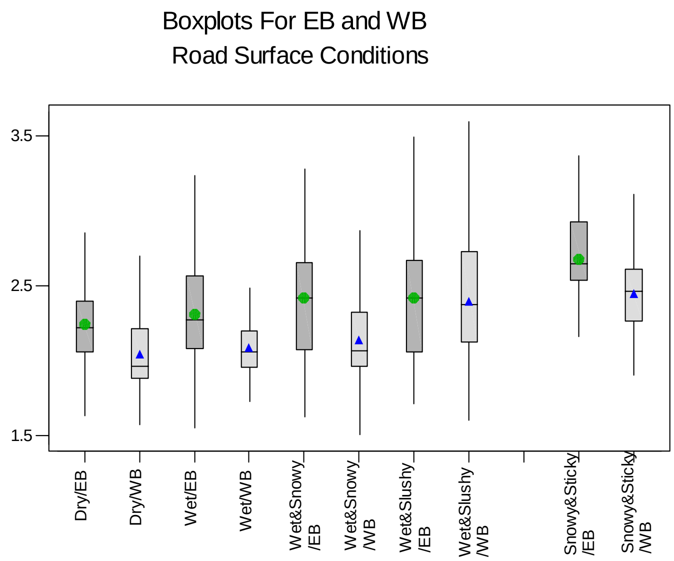
Variable	N	Mean	Median	TrMean	StDev	SE Mean
Dry/WB	49	1.997	2.035	1.945	1.255	0.179
Dry/EB	34	2.749	2.460	2.712	1.556	0.267
Wet/WB	38	2.034	1.820	1.987	1.340	0.217
Wet/EB	43	2.094	1.693	2.013	1.330	0.203
Wet&Snowy/WB	60	2.066	1.880	2.013	1.382	0.178
Wet&Snowy/EB	50	2.564	2.263	2.480	1.633	0.231
Wet&Slushy/WB	59	1.861	2.025	1.840	1.151	0.150
Wet&Slushy/EB	34	2.445	2.643	2.482	1.131	0.194
Slushy/WB	37	2.195	2.005	2.150	1.214	0.200
Slushy/EB	25	2.788	2.660	2.676	1.766	0.353
Snowy&Sticky/WB	45	2.798	2.650	2.777	1.686	0.251
Snowy&Sticky/EB	24	3.373	3.735	3.387	1.775	0.362

As can be seen, there exists some amount of skewness in both the startup lost-times and the saturation headways data for both winter seasons, with the data skewed to the right. The comparative boxplots in Figures 3 and 4 further confirms this fact for the two traffic flow parameters. However, the low standard error of the mean for the saturation headways and startup lost times show that the sample mean values obtained will be close to the true population mean for both saturation headways and startup lost-times values. Considering the standard deviation values, it can be seen that the data is less spread about the mean saturation headways than about the mean startup lost times. In either case, there exists some level of variability in the data, which is to be expected.

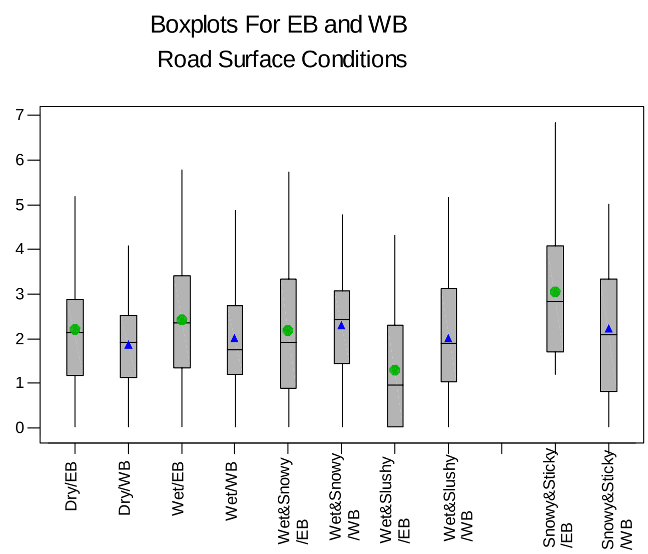
From the comparative boxplots for the 2002/2003 saturation headways (Figure 3a), it can be seen that the mean saturation headways were higher for the EB direction than for the WB direction.

Figure 3. Boxplots for 2002/2003 Saturation Headway and Startup Lost Time

Saturation Headway (Figure 3a)



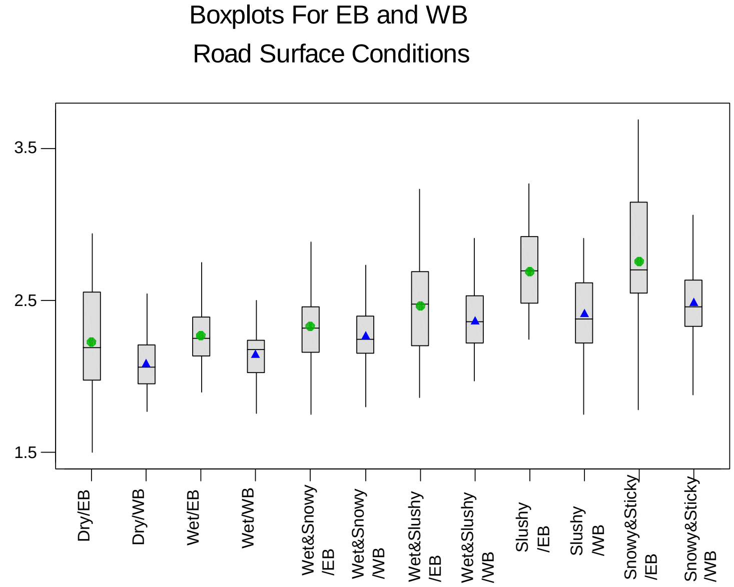
Startup Lost Time (Figure 3b)



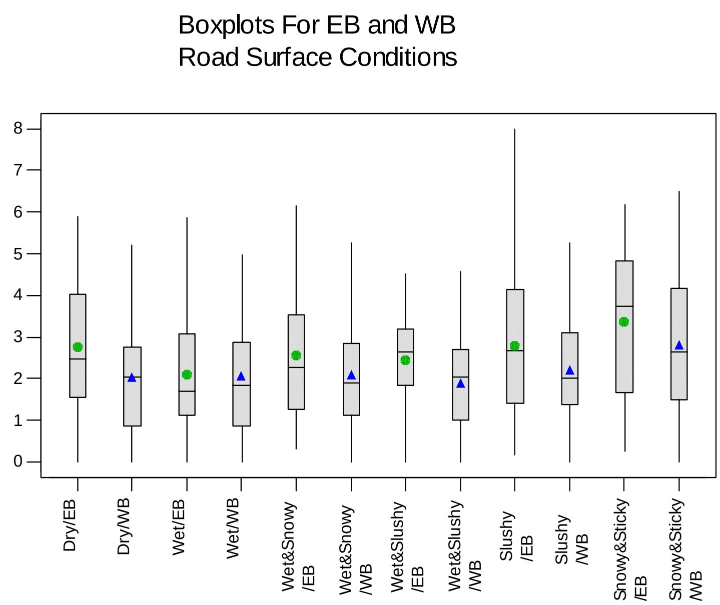
This is to be expected because of the presence of the significant grade in the EB direction. It can also be seen that there appears to be significant differences between the mean values for the different road surface conditions (a more quantitative assessment of these differences will be given later in this paper). For the startup lost times, the differences appear to be less pronounced (Figure 3b). Similar observations can be made regarding the 2003/2004 winter season data (Figure 4).

Figure 4. Boxplots for 2003/2004 Saturation Headway and Startup Lost Time

Saturation Headway (Figure 4a)



Startup Lost Time (Figure 4b)



3.2.2. Inferential Statistical Analysis

To better quantify the differences between the values of the saturation headways and startup lost times under the six different weather/road surface conditions, an Analysis of Variance (ANOVA) was performed on the data points using a 95% Confidence Interval (CI) at a 0.05 significance level. The EB direction was analyzed separately from the WB direction for all six weather/road surface conditions. First, a one-way ANOVA was performed on the 2002-2003 data points and then on the 2003-2004 data points.

<u>*3.2.2.1. ANOVA Results for Saturation Headways*</u>

Tables 6 and 7 show the one-way ANOVA results for the saturation headways for both the 2002/2003 and 2003/2004 winter seasons.

Table 6. ANOVA Results for 2002/2003 Saturation Headways

EB Direction Road Surface Conditions

```
Analysis of Variance
Source     DF        SS        MS       F        P
Factor      4    6.6012    1.6503   17.30    0.000
Error     472   45.0321    0.0954
Total     476   51.6332
                                         Individual 95% CIs For Mean
                                         Based on Pooled StDev
Level             N      Mean     StDev  ---+---------+---------+---------+---
Dry/EB          189    2.2397    0.2332  (--*--)
Wet/EB          139    2.3100    0.3112     (--*---)
Wet&Snowy/EB     59    2.4153    0.3816          (----*----)
Wet&Slushy/EB    54    2.4144    0.4313          (----*----)
Snowy&Sticky/EB  36    2.6714    0.2992                          (-----*-----)
                                          ---+---------+---------+---------+---
Pooled StDev =    0.3089                    2.24      2.40      2.56      2.72
```

WB Direction Road Surface Conditions

```
Analysis of Variance
Source     DF        SS        MS       F        P
Factor      5   34.7458    6.9492   96.12    0.000
Error     970   70.1284    0.0723
Total     975  104.8742
                                         Individual 95% CIs For Mean
                                         Based on Pooled StDev
Level             N      Mean     StDev  -+---------+---------+---------+-----
Dry/WB          175    2.0388    0.2529   (-*-)
Wet/WB          282    2.0761    0.1714     (-*)
Wet&Snowy/WB    187    2.1287    0.2763        (*-)
Wet&Slushy/WB   136    2.3917    0.4013                    (--*-)
Slushy/WB       101    2.5794    0.3113                             (--*--)
Snowy&Sticky/WB  95    2.4407    0.2334                      (--*--)
                                          -+---------+---------+---------+-----
Pooled StDev =   0.2689                  2.00      2.20      2.40      2.60
```

Table 7. ANOVA Results for 2003/2004 Saturation Headways

EB Direction Road Surface Conditions

Analysis of Variance

```
Source     DF       SS        MS       F        P
Factor      5   22.3586    4.4717    59.85    0.000
Error     744   55.5877    0.0747
Total     749   77.9463
                                          Individual 95% CIs For Mean
                                          Based on Pooled StDev
Level                N      Mean     StDev  -+---------+---------+---------+-----
Dry/EB             153    2.2236    0.2960  (-*-)
Wet/EB             206    2.2672    0.2079    (-*-)
Wet&Snowy/EB       152    2.3322    0.2106       (--*-)
Wet&Slushy/EB      108    2.4643    0.3144              (-*--)
Slushy/EB           80    2.6906    0.2904                         (--*--)
Snowy&Sticky/EB     51    2.7547    0.4352                           (---*--)
                                            -+---------+---------+---------+-----
Pooled StDev =   0.2733                     2.20      2.40      2.60      2.80
```

WB Direction Road Surface Conditions

Analysis of Variance

```
Source     DF       SS        MS       F        P
Factor      5   24.0757    4.8151   107.26    0.000
Error    1321   59.3001    0.0449
Total    1326   83.3758
                                          Individual 95% CIs For Mean
                                          Based on Pooled StDev
Level                N      Mean     StDev  ---+---------+---------+---------+---
Dry/WB             265    2.0824    0.1789  (-*-)
Wet/WB             155    2.1419    0.1576      (-*-)
Wet&Snowy/WB       269    2.2623    0.2027              (-*-)
Wet&Slushy/WB      325    2.3621    0.2063                     (*-)
Slushy/WB          179    2.4098    0.2651                        (-*-)
Snowy&Sticky/WB    134    2.4823    0.2703                            (-*--)
                                            ---+---------+---------+---------+---
Pooled StDev =   0.2119                       2.10      2.25      2.40      2.55
```

As can be seen from the tables, based upon a 95% CI, the *p-value* (0.000) for both the EB and WB directions is less than the significance level (*alpha=0.05)*. This means that there is enough evidence from the data to conclude that the mean saturation headways are different for the different weather/road surface conditions, for both the EB and WB directions. The CI plots also clearly show these differences. The trend of increasing saturation headways with an increase in weather severity is somewhat clear in the 2003/2004 data, compared to the 2002/2003 data.

3.2.2.2. Multiple Comparison Test Results for Saturation Headways

A Multiple Comparison Test, using Tukey's Pairwise Comparison, was conducted to determine which weather/road surface conditions actually differed from each other. Generally for the

Multiple Comparison Test, an interval is computed for the difference in mean between each pair of data sets. If the **zero** value lies within the interval computed, this means that there is **no** statistically significant difference between the means of the two data sets considered. However, if the zero value is **not** within the range computed for the interval, the means of the two data sets are regarded as statistically significantly different.

The results of the Multiple Comparison Test for the 2002/2003 saturation headways are shown in Table 8.

Table 8. Multiple Comparison Method for 2002/2003 Saturation Headways

Multiple Comparison Method for WB Road Surface Conditions

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00447
Critical value = 4.03

Intervals for (column level mean) - (row level mean)

	Dry/WB	Slushy/WB	Snowy& Sticky/WB	Wet& Slushy/WB	Wet& Snowy/WB
Slushy/WB	-0.6363 -0.4448				
Snowy& Sticky/WB	-0.4995 -0.3042	0.0291 0.2482			
Wet& Slushy/WB	-0.4404 -0.2653	0.0871 0.2883	***-0.0534*** ***0.1515***		
Wet& Snowy/WB	-0.1704 -0.0093	0.3561 0.5453	0.2155 0.4086	0.1767 0.3494	
Wet/WB	***-0.1110*** ***0.0365***	0.4144 0.5921	0.2737 0.4555	0.2356 0.3956	***-0.0197*** ***0.1248***

Multiple Comparison Method for EB Road Surface Conditions

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00658
Critical value = 3.86

Intervals for (column level mean) - (row level mean)

	Dry/EB	Snowy& Sticky/EB	Wet& Slushy/EB	Wet& Snowy/EB
Snowy& Sticky/EB	-0.5851 -0.2785			
Wet& Slushy/EB	-0.3049 -0.0447	0.0756 0.4384		
Wet& Snowy/EB	-0.3014 -0.0499	0.0779 0.4345	***-0.1596*** ***0.1579***	
Wet/EB	***-0.1645*** ***0.0239***	0.2038 0.5191	***-0.0307*** ***0.2397***	***-0.0257*** ***0.2363***

The results for the WB direction are presented first, since for the 2002/2003 season this approach resulted in a larger number of data points for the different road surface conditions. The larger data set in turn, increases our confidence in the conclusions derived from the data. As can be seen, for the WB approach, all comparisons showed statistical significant differences, with **the exception of** the following three pairs of conditions. They are, the *Dry* versus the *Wet* condition, the *Wet* versus the *Wet and Snowy* condition, and the *Wet and Slushy* versus the *Snowy and Sticky* condition. For the EB approach, the results were generally similar to the WB approach. However, the *Wet and Slushy* condition did not show significant differences with either the *Wet* or the *Wet and Snowy* conditions, but did show significant differences with the *Snowy and Sticky* condition.

For the 2003-2004 winter season, for the WB approach, all comparisons showed significant differences, with **the exception of** the following two pairs of conditions: *Dry Condition* versus the *Wet Condition* and *Wet and Slushy Condition* versus the *Slushy in Wheel Paths Condition*. For the EB approach, the *Dry Condition* versus the *Wet Condition,* the *Wet Condition* versus *Wet and Snowy Condition,* and *Slushy in Wheel Paths Condition* versus *Snowy and Sticky* **did not show** any statistical significant differences in their means. The rest of the comparisons **showed** statistical significant differences in their means. This provides further evidence that inclement weather does have significant impact saturation headways.

Table 9 compares the results from the Multiple Comparison Tests conducted for the two winter seasons.

Table 9. Weather Conditions Pairs NOT Showing Statistical Differences for Saturation Headways

Condition Pairs	**2002/2003 Season**		**2003/2004 Season**	
Dry versus Wet	**X**	**X**	**X**	**X**
Wet versus Wet & Snowy	**X**	**X**	**X**	
Wet versus Wet & Slushy	**X**			
Wet & Slushy versus Snowy & Sticky		**X**		
Wet & Snowy versus Wet & Slushy	**X**			
Slushy in WP versus Snowy & Sticky			**X**	
Slushy in WP versus Wet & Slushy				**X**

Specifically, the table lists those pairs of weather/road surface conditions that were found to be **NOT** statistically significantly different, to help draw some concrete conclusions from the results. As can be seen, the comparison shows that the mean saturation headways for *Dry* versus *Wet* and *Wet* versus *Wet & Snowy* conditions do not show statistical significant differences for almost all approaches and for both winter seasons. As a result, it appears that the mean saturation headways are not statistically different between each of these two pairs of weather conditions. With the other comparisons, the results presented do not provide enough evidence to justify similar conclusions, since typically only one case out of four did not show statistically significant differences.

3.2.2.3. ANOVA Results for Startup Lost Times

The one-way ANOVA results for the startup lost time are presented in Tables 10 and 11 for the two winter seasons.

Table 10. ANOVA Results for 2002/2003 Startup Lost Times

EB Direction Road Surface Conditions

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	4	38.05	9.51	4.75	**0.001**
Error	173	346.70	2.00		
Total	177	384.76			

```
                                      Individual 95% CIs For Mean
                                      Based on Pooled StDev
Level           N      Mean     StDev  ---+---------+---------+---------+---
Dry/EB         45     2.203     1.179             (---*---)
Wet/EB         56     2.421     1.409               (---*---)
Wet&Snowy/EB   32     2.177     1.653            (----*----)
Wet&Slushy/EB  32     1.293     1.323   (----*----)
Snowy&Sticky   13     3.042     1.764                  (------*-------)
                                       ---+---------+---------+---------+---
Pooled StDev =    1.416                  1.0       2.0       3.0       4.0
```

WB Direction Road Surface Conditions

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	5	7.49	1.50	1.01	**0.409**
Error	293	432.63	1.48		
Total	298	440.13			

```
                                         Individual 95% CIs For Mean
                                         Based on Pooled StDev
Level             N      Mean     StDev  ---------+---------+---------+-------
Dry/WB           35     1.839     1.005  (-----------*----------)
Wet/WB           64     1.980     1.125         (--------*-------)
Wet&Snowy/WB     72     2.280     1.131                  (-------*-------)
Wet&Slushy/WB    51     2.000     1.293         (--------*---------)
Slushy/Wet/WB    41     1.901     1.329     (---------*----------)
Snowy&Sticky/WB  36     2.199     1.449            (-----------*----------)
                                         ---------+---------+---------+-------
Pooled StDev =    1.215                         1.75      2.10      2.45
```

Table 11. ANOVA Results for 2003/2004 Startup Lost Time

EB Direction Road Surface Conditions

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	5	27.87	5.57	2.40	**0.039**
Error	204	474.34	2.33		
Total	209	502.22			

```
                                        Individual 95% CIs For Mean
                                        Based on Pooled StDev
Level            N      Mean     StDev  -------+---------+---------+---------
Dry/EB          34     2.749     1.556           (------*-------)
Wet/EB          43     2.094     1.330  (------*-----)
Wet&Snowy/EB    50     2.564     1.633          (-----*-----)
Wet&Slushy/EB   34     2.445     1.131       (------*------)
Slushy/EB       25     2.788     1.766          (--------*-------)
Snowy&Sticky/EB 24     3.373     1.775                  (--------*--------)
                                        -------+---------+---------+---------
Pooled StDev =    1.525                       2.10      2.80      3.50
```

WB Direction Road Surface Conditions

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	5	25.91	5.18	2.87	**0.015**
Error	282	509.80	1.81		
Total	287	535.71			

```
                                        Individual 95% CIs For Mean
                                        Based on Pooled StDev
Level            N      Mean     StDev  ----------+---------+---------+------
Dry/WB          49     1.997     1.255    (-------*-------)
Wet/WB          38     2.034     1.340    (--------*-------)
Wet&Snowy/WB    60     2.066     1.382      (------*------)
Wet&Slushy/WB   59     1.861     1.151  (------*------)
Slushy/WB       37     2.195     1.214       (--------*--------)
Snowy&Sticky/WB 45     2.798     1.686                    (-------*-------)
                                        ----------+---------+---------+------
Pooled StDev =    1.345                         2.00      2.50      3.00
```

As can be seen, for the 2002/2003 season, the results indicate no statistically significant differences for the WB direction, but statistically significant differences for the EB direction. For the 2003-2004 season, statistical differences are detected for both directions using a 95% CI, but using a 99% CI, however, would indicate that there are no significant differences. A careful examination of the CI plots in Tables 8 and 9 also shows that with the exception of the snowy and sticky condition for the 2003-2004 winter season, inclement weather does not seem to have a significant impact on startup lost time. In addition, no specific trend can be identified. In comparing the significance of the inclement weather impact on startup lost time to that obtained for the saturation headways, the impact on the startup lost times appears to be much less pronounced.

3.2.2.4. Multiple Comparison Test Results for Startup Lost Times

For the 2002/2003 WB data, there was no need to perform a *Multiple Comparison Test,* since no statistical significant differences were detected among the different weather/road surface conditions. For the EB data, the Multiple Comparison Test revealed that, with the exception of the comparisons of the *Snowy and Sticky* versus *Wet and Slushy Conditions*, *Wet* versus *Wet and Slushy Conditions* and *Dry* versus *Wet and Slushy Conditions*, all other paired comparisons **did not** show any statistical significant differences between them because they had **zero** in their interval (it should be noted here that the value obtained for the startup lost time for the Wet and Slushy condition is rather low, which raises some concerns about the validity of the data collected for that weather condition, and could explain the statistical differences detected). This tends to demonstrate that inclement weather does not appear to have a significant impact on the startup lost time at signalized intersections justifying the conclusions made earlier.

For the 2003/2004 season and for both the WB and EB data points, all comparisons but with a few exceptions, showed **no** statistically significant differences in their means. The **exceptions** showing statistically significant differences in their means are, for WB: *Snowy and Sticky Condition* versus the *Dry Condition* and *Wet and Slushy Condition* versus *Snowy and Sticky Condition*, and for EB: *Snowy and Sticky Condition versus* the *Wet Condition*. This reinforces the point that inclement weather does not appear to have a significant impact on the values of the startup lost times, with the exception of perhaps the snowy and sticky condition.

3.2.3. Comparing Data Collected from the Two Winter Seasons

In order to validate the results and the conclusions made earlier, a two way ANOVA was performed on the 2002/2003 and 2003/2004 data points for both the saturation headway and the startup lost time data. Table 12 shows the two-way ANOVA results for the saturation headways for both the EB and the WB directions. In the table, the term "year" refers to the two winter seasons, while the term "levels" to the different weather/road surface conditions. If the data were accurate, one would expect the "year" to have **no statistically significant** impact on the saturation headways, since the data were collected from the same intersection in the two years. On the other hand, one would expect the "levels" or the different weather conditions to have a statistically significant impact, as was demonstrated when each year data set was considered separately.

As can be seen from Table 10, using a 95% CI reveals that the *p-values* for both the EB and WB directions are greater than an alpha value of 0.05. This means that, as expected, there exist no statistical significant differences for the effect of year on mean saturation headways. This helps validates the accuracy of the data collection and reduction effort. For the effect of levels on mean saturation headways, *p-values* less than 0.05 were obtained, indicating that there exist statistical significant differences for the effect of levels or the different weather/road conditions on mean saturation headways, as discussed before.

Table 12. Two Way ANOVA Results for Saturation Headways

EB Direction Road Surface Conditions

Factor	Type	Levels	Values
Year	fixed	2	2002-2003 2003-2004
Levels	fixed	5	EB dry EB Snowy&Sticky EB Wet EB Wet&Slushy EB Wet&Snowy

Analysis of Variance for Saturation Headways, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Year	1	0.0156	0.0002	0.0002	0.00	**0.965**
Levels	4	19.5782	18.1818	4.5455	54.93	**0.000**
Error	1135	93.9254	93.9254	0.0828		
Total	1144	114.1055				

WB Direction Road Surface Conditions

Factor	Type	Levels	Values
Year	fixed	2	2002-2003 2003-2004
Levels	fixed	6	WB Dry WB Slushy WB Snowy&Sticky WB Wet WB Wet&Slushy WB Wet&Snowy

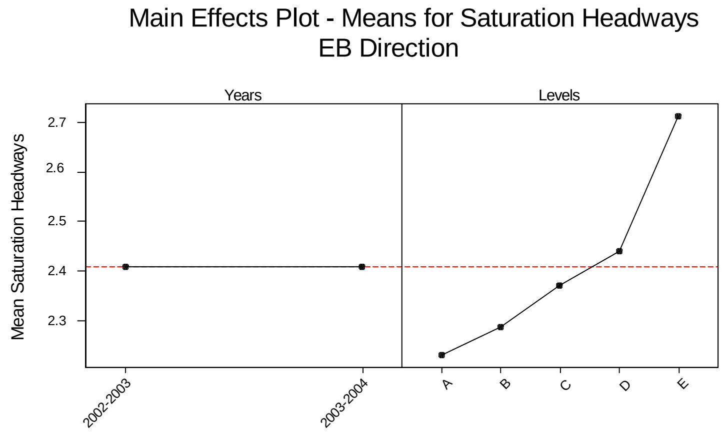
Analysis of Variance for Shwy, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Year	1	2.3516	0.0760	0.0760	1.36	**0.244**
Levels	5	54.4786	55.6669	11.1334	198.61	**0.000**
Error	2280	127.8075	127.8075	0.0561		
Total	2291	188.5971				

The same conclusions can be drawn from the factor plots (Figure 5). As can be seen, the line joining both years lies approximately on the dotted line (average), confirming that there exist no effect of the "year" on mean saturation headways for both approaches. Also, for the effect of "levels" on mean saturation headways, there is an increasing trend in mean saturation headways from the *Dry Condition* right to the *Snowy and Sticky Condition*, and in that order. This confirms the conclusions made earlier.

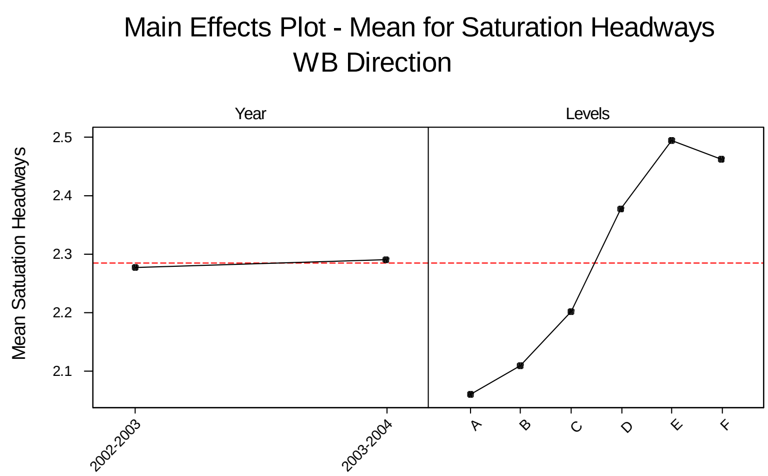
Figure 5. Factor Plots for Main Effects for Year and Levels for Saturation Headways

EB Direction Saturation Headways (Figure 4a)



A: Dry Condition, **B**: Wet Condition, **C**: Wet and Snowy Condition, **D**: Wet and Slushy Condition, and **E:** Snowy and Sticky Condition.

WB Direction Saturation Headways (Figure 4b)



A: Dry Condition, **B**: Wet Condition, **C**: Wet and Snowy Condition, **D**: Wet and Slushy Condition: **E**: Slushy in Wheel Paths Condition and **F**: Snowy and Sticky Condition

Figure 6 compares the mean values for the saturation headway between the two winter seasons for the EB and WB directions, for the different weather conditions.

Figure 6. Comparing Saturation Headways for the Two Winter Seasons

Figure 6a: EB Direction

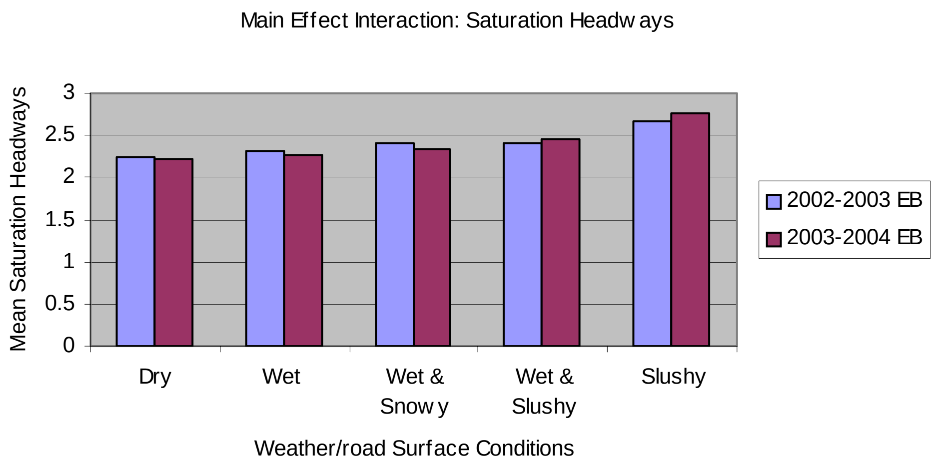
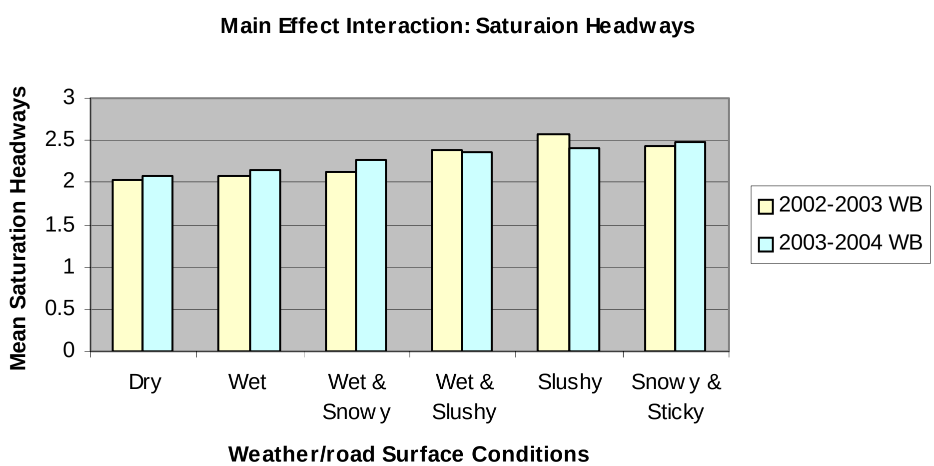


Figure 6b: WB Direction



As can be seen, the values appear to be very close to one another, which further validates the accuracy of the data collection and reduction effort. The differences between the corresponding mean values for the two winter seasons ranged between 0.02 seconds for the EB dry condition to 0.13 seconds for the WB wet and snowy condition, with an average value of 0.06 seconds.

3.2.4. Summary of Results

Table 13 summarizes the values obtained for the mean saturation headways and the mean startup lost times for the six different road surface conditions, from the two winter seasons. The Table also computes the corresponding saturation flow rates, and the reduction in the saturation flow rate compared to the dry condition, for each weather/road surface condition. Given the different grades for the EB and WB directions, the results are recorded separately for each approach.

Table 13. Summary of Values Obtained for Startup Lost Time and Saturation Headways

Table 13a: Values for 2002/2003 Winter Season

Road Condition	Startup Lost Time		Saturation Headway (Saturation Flow Rate) [1]		% Reduction in Saturation Flow Rate	
	EB	WB	EB	WB	EB	WB
1. Dry	2.20	1.84	2.24 (1607)	2.04 (1766)	0%	0%
2. Wet	2.42	1.98	2.31 (1558)	2.08 (1734)	3%	2%
3. Wet and Snowy	2.18	2.28	2.42 (1490)	2.13 (1691)	7%	4%
4. Wet and Slushy	1.29	2.00	2.41 (1491)	2.39 (1505)	7%	15%
5. Slushy in WP	---[2]	1.90	---[2]	2.58 (1396)	---[2]	21%
6. Snowy and Sticky	3.04	2.20	2.67 (1348)	2.44 (1475)	16%	16%

Table 13b: Values for the 2003/2004 Winter Season

Road Condition	Startup Lost Time		Saturation Headway (Saturation Flow Rate) [1]		% Reduction in Saturation Flow Rate	
	EB	WB	EB	WB	EB	WB
1. Dry	2.75	2.00	2.22 (1622)	2.08 (1731)	0%	0%
2. Wet	2.09	2.03	2.27 (1586)	2.14 (1682)	2%	3%
3. Wet and Snowy	2.56	2.07	2.33 (1545)	2.26 (1593)	5%	9%
4. Wet and Slushy	2.45	1.86	2.46 (1463)	2.36 (1525)	11%	13%
5. Slushy in WP	2.79	2.20	2.69(1338)	2.41 (1494)	21%	16%
6. Snowy and Sticky	3.37	2.80	2.76 (1304)	2.48 (1452)	24%	19%

1 Units: Saturation Headway (seconds per vehicle), Startup lost time (seconds)
[2] Values not available

As can be seen, for both winter seasons, there exists an increasing trend in mean saturation headways for both the EB and the WB directions with increasing severity in weather/road surface conditions. This trend appears to be more consistent with the 2003/2004 winter data than with the 2002-2003 winter data, which has some discrepancies. In addition, it can be seen that the mean saturation headways for the EB direction are greater than for the WB direction for both winter seasons, which illustrates the impact that the grade has on the values of mean saturation headways obtained. For the startup lost times, as discussed before, the results from both winter seasons did not show any significantly increasing trend with increasing severity in inclement weather conditions for the EB and WB directions, with the exception of the startup lost time for the snowy and sticky conditions, which appear to be significantly higher than the other conditions.

3.3. Comparison to Values Reported in The Literature

With the impact of inclement weather on traffic flow parameters quantified, the next step was to find out how the values obtained in this study for Northern New England conditions compare to the values obtained from the few other previous studies reported in the literature that were conducted in other parts of the country. Four such studies could be identified. These were conducted in: (1) Salt Lake City, Utah (Perrin et al., 2001); (2) Fairbanks, Alaska (Bernardin Lochmueller and Associates, Inc., 1995); (3) Anchorage, Alaska (Bernardin Lochmueller and Associates, Inc., 1995); and (4) Minneapolis, Minnesota (Maki, 1999).

The comparison between the results from the current study and those from other studies had to be based on the percent reduction in saturation flow rates, and not on the absolute value of the traffic flow parameter obtained, since the base conditions for the intersections considered in the different studies varied. In addition, the comparison was limited to reductions in the saturation flow rate, since our study did not show that the start up lost time is significantly impacted by inclement weather, except for the snowy and sticky condition.

Table 14. Comparing Saturation Flow Rate Reductions

Table 14a

	Burlington, Vermont		**Salt Lake City, Utah**
Weather Condition	**EB Direction**	**WB Direction**	
1. Dry	0 %	0 %	0 %
2. Wet	3 %	2 %	6 %
3. Wet and Snowy	7 %	7 %	11 %
4. Wet and Slushy	9%	15 %	18 %
5. Slushy in Wheel Paths	---	21 %	18 %
6. Snowy and Sticky	22 %	19 %	20 %

Table 14b

					Burlington, Vermont			
	Salt Lake, Utah	**Fairbanks, Alaska**	**Anchorage, Alaska**	**Minneapolis, Minnesota**	**2002/2003**		**2003/2004**	
					EB	**WB**	**EB**	**WB**
Normal (Dry)	1808	1792	1816	1800	1607	1766	1622	1731
Inclement	1432	1538	1600	1600	1443	1517	1413	1516
%Reduction	**17%**	**14%**	**12%**	**11%**	**10%**	**14%**	**12%**	**13%**

Table 14 shows the results of this comparison. Table 14a compares the current study's results (the values reported are the averages of the two winter seasons) to those of the Salt Lake study. In general, the results obtained from this study are quite comparable to the Salt Lake study's results. However, the Burlington, Vermont results appear to be slightly less than for Salt Lake City, especially for the conditions 2, 3 and 4.

The Alaska and Minnesota studies only considered snow events with accumulations of 3 inches or more. They then found the corresponding average saturation flow rate under those conditions, without specifically categorizing the weather/road surface conditions into one of the six different categories that the current study considered. Therefore, to allow for comparing the Alaska and Minnesota studies and our study, the current study assumed that the inclement weather conditions considered in the Alaska and Minnesota studies correspond to averages for conditions 3 through 6. The results are shown in Table 14b. As can be seen, there is a very close agreement between results from Burlington, Vermont and those from Alaska and Minnesota. The results from Salt Lake City, while somewhat higher, are still quite close to the current study's results.

3.4 Conclusions

From the above results, the following conclusions can be made:

1. There is enough evidence to suggest that inclement weather has a significant impact on the values of saturation headways, and hence saturation flow rates at signalized intersections;
2. Out of the six different weather/road surface conditions considered in this study, conditions four through six (i.e. wet and slushy, slushy in wheel paths, and snowy and sticky) appear to have the most significant impact on saturation flow rate;
3. Values for startup lost times, with the exception of the snowy and sticky condition, do not appear to be significantly impacted by inclement weather in comparison to the significant impact inclement weather has on saturation headways;
4. The Multiple Comparison Test reveals that the values of the saturation headways under the dry condition as compared to the wet condition, and the wet condition compared to the wet and snowy condition are not statistically significantly different for both winter seasons;
5. The impact of inclement weather on saturation flow rates appears to be a function of the grade of the approach;
6. The percent reduction values in the saturation flow rate at signalized intersections obtained for Burlington, Vermont closely agrees with the values reported in the literature for the states of Alaska, Minnesota and Utah;
7. The significant impact that inclement weather has on values of saturation headways and hence saturation flow rates at signalized intersections suggest that the implementation of "special" timing plans for inclement weather might be beneficial from both an operational as well as a safety standpoint. Further research, however, is needed to verify this suggestion.

CHAPTER 4 – OPERATIONAL BENEFITS OF SPECIAL TIMING PLANS FOR INCLEMENT WEATHER

Having established the impact of inclement weather on traffic flow parameters at signalized intersections, the next step in the study was to evaluate the likely benefits of implementing "special" timing plans for inclement weather. This step constitutes the focus of the current chapter which is dedicated to describing the methodology used, as well as to presenting and discussing the results obtained. The chapter is divided into two sections. Section one describes the methodology followed and the four case studies considered in this research. The results from the analysis are then presented and discussed in section two.

4.1 Methodology

As mentioned above, the focus of this stage of the study is on evaluating the likely operational benefits of implementing "special" signal plans for the different road surface conditions that can develop during inclement weather. The weather/road surface conditions considered are: (1) Dry Condition; (2) Wet Condition; (3) Wet and Snowy Condition; (4) Wet and Slushy Condition; (5) Slushy in Wheel Paths Condition; and (6) Snowy and Sticky Condition. To achieve this objective, four signalized arterial corridors, two from the State of Vermont and two from the State of Connecticut, were selected as case studies and optimal signal plans were then developed for the two corridors for the six different weather/road surface conditions. The likely benefits of implementing "special" plans for inclement weather were then determined by comparing travel conditions under the "special" weather-specific optimal timing plans, to travel conditions assuming the optimal plan developed for the "dry" weather condition plan would remain unchanged.

The methodology thus consisted of the following four tasks:

1. Selecting the four case studies.
2. Developing and calibrating the analytical and simulation-based tools required for carrying out the study;
3. Developing optimal signal plans for the different weather/road surface conditions; and
4. Determining the likely operational benefits of implementing weather-specific optimal timing plans for the four corridors, using different simulation models.

These steps are briefly discussed below.

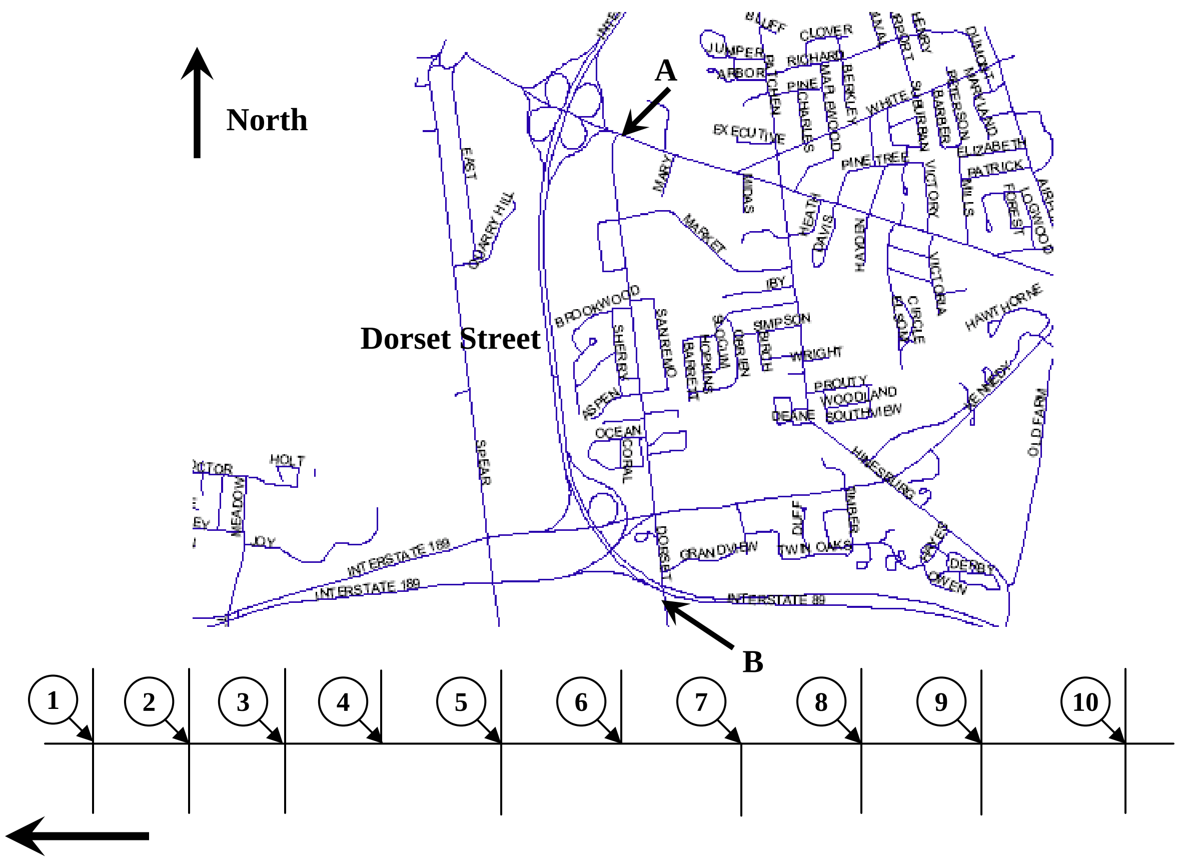
4.1.1. Selection of Four Case Studies

The goal here was to select four case studies for the purposes of evaluating the likely operational benefits of implementing weather-specific timing plans. In selecting those four case studies, the criteria established were to select four arterial signalized systems, with a minimum of three and a maximum of ten intersections in each, and to select two corridors from the State of Vermont, and another two from the State of Connecticut. The selected corridors are briefly described below.

4.1.1.1. Case Study 1 - Dorset Street, South Burlington, Vermont

A segment of Dorset Street in the City of South Burlington, Vermont was selected to serve as the first case study for assessing the benefits of implementing special timing plans for inclement weather conditions. Figure 7 below shows a schematic of the segment of Dorset Street considered for this study. As can be seen, the selected segment of Dorset Street extends from one end of the arrow A to the other end B, with a total length of 1.725 kilometers (1.08 miles). Points A and B are Dorset Street/Williston road intersection and Dorset Street/Kennedy Drive intersection, respectively. The signalized network consists of a total of eight signalized and two unsignalized intersections, and serves the dual purpose of providing access to abutting commercial land use developments while accommodating the through traffic movement going through the City of South Burlington. Out of the eight signalized intersections, six intersections are coordinated. All the signalized intersections are actuated controllers.

Figure 7. Dorset Street in South Burlington, Vermont



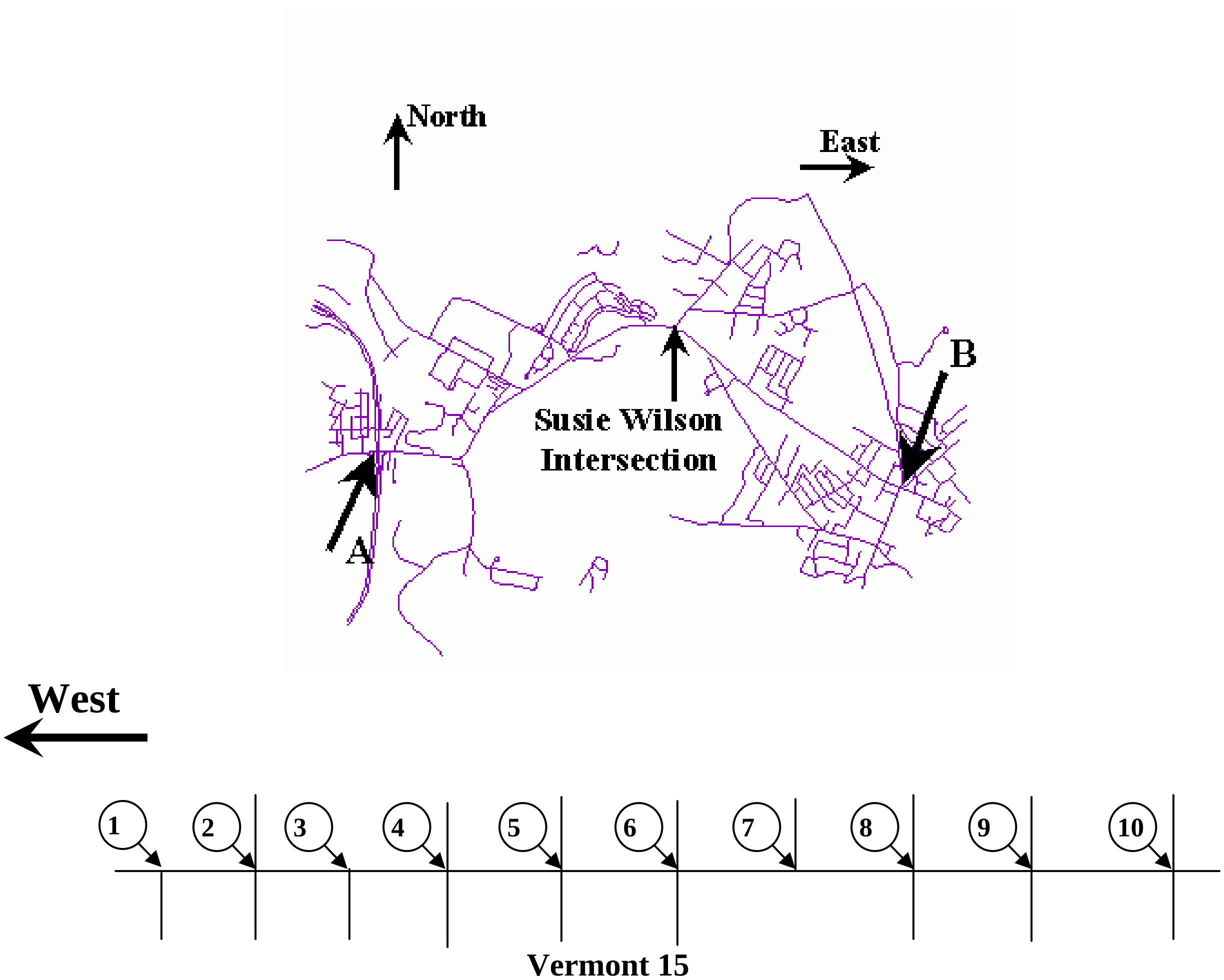
North

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 intersections

4.1.1.2. Case Study 2 - Vermont Route 15, Chittenden County, Vermont

The second case study considered was the segment of Vermont Route 15 shown by the schematic in figure 8 below. Vermont Route 15 serves both mobility through the town of Colchester and accessibility to commercial centers and neighboring communities. This corridor has longer segments connecting intersections than the segment selected for case study 1 (Dorset Street). From figure 8, the segment of Vermont 15 has a total length of 5.836 kilometers (3.63 miles). The points A and B are the intersection between, I-89 exit with Vermont 15 (where the corridor starts), and Five corners with Vermont 15 (where the corridor ends), respectively. Ten signalized intersections were abstracted from this arterial corridor. All the signalized intersections along the Vermont 15 corridor were actuated controllers.

Figure 8. Vermont 15 in Chittenden County, Vermont

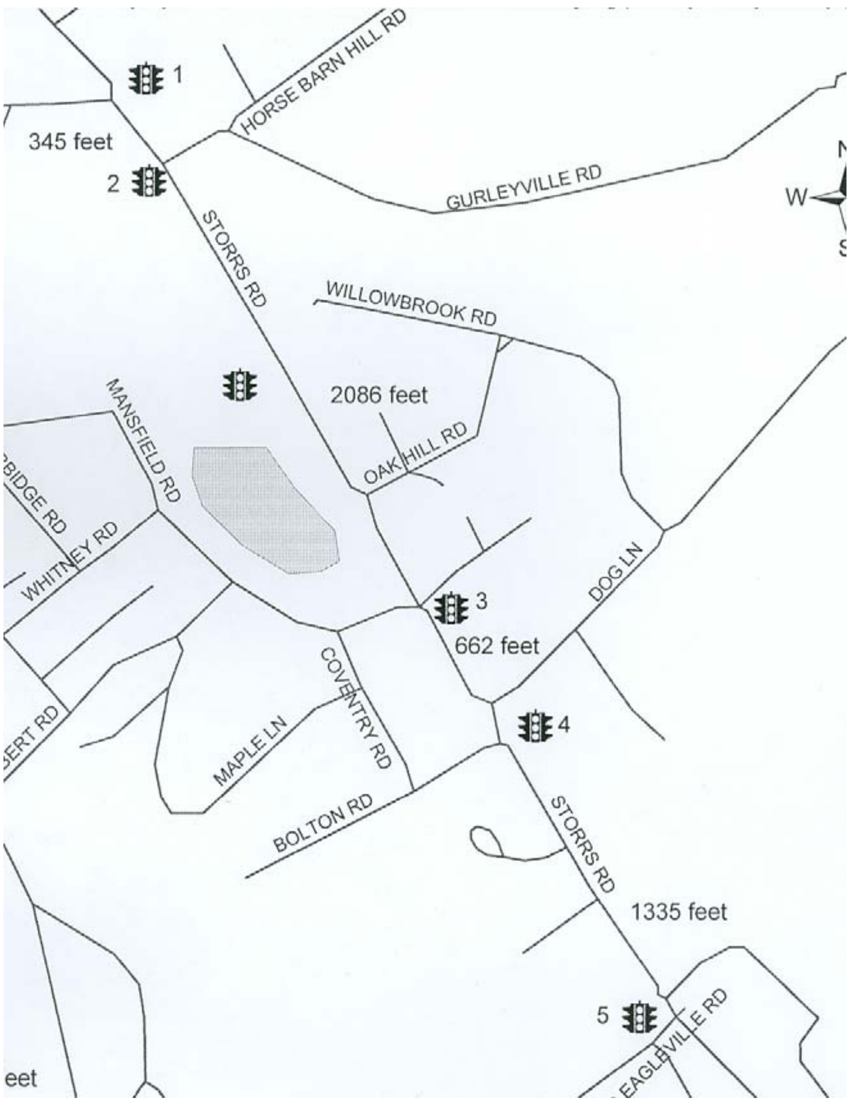


Intersections 1 to 10 are actuated signalized intersections.
Intersections 1 to 8 are coordinated.
Intersections 9 to 10 are uncoordinated.

4.1.1.3. Case Study 3 – Storrs Road, Storrs, Connecticut

The third case study considered was a segment of Route 195 (also known as Storrs Road) which goes through thee University of Connecticut Campus in Storrs, Connecticut. The segment has five signalized intersections (Figure 9). Out of the five signalized intersections, only one intersects with a state route (route 275), the remaining four intersect with local roads. The segment considered had a total length of 4428 feet (0.84 miles).

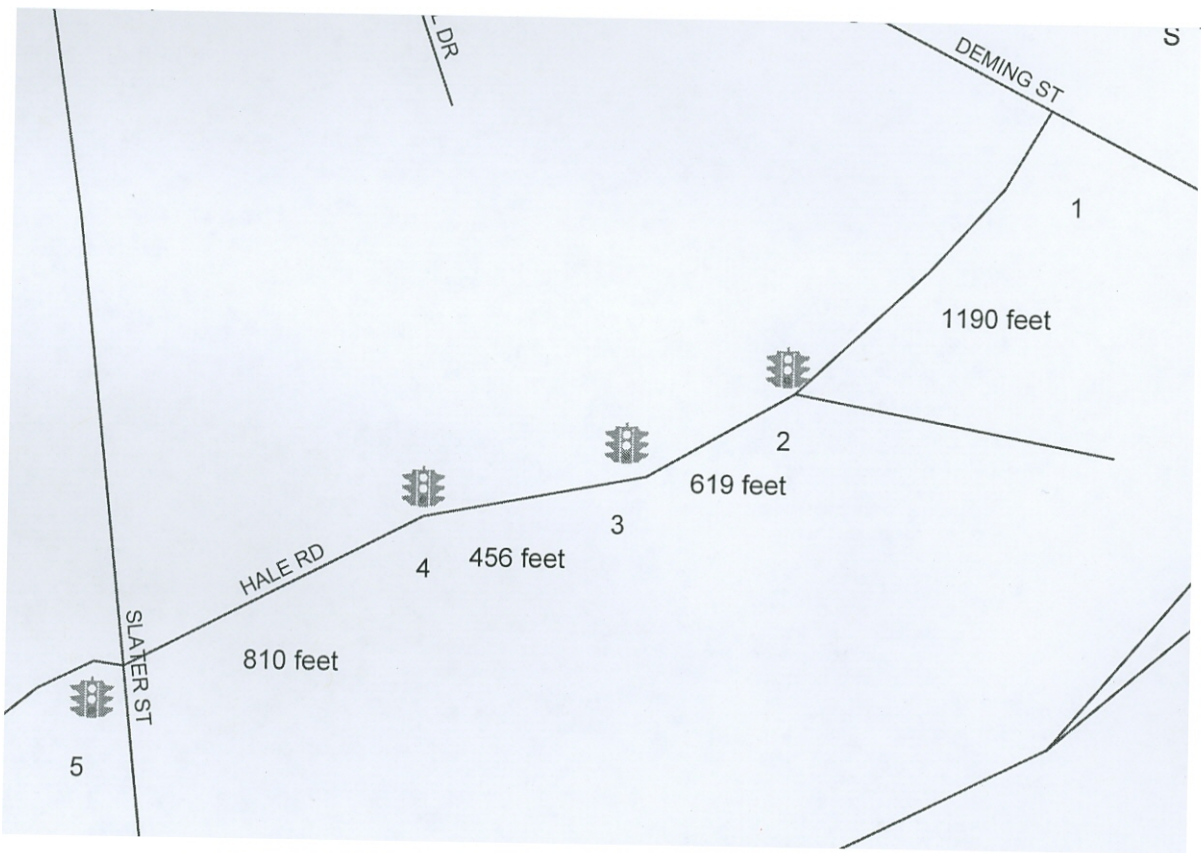
Figure 9. Storrs Road in Storrs, Connecticut



4.1.1.4. Case Study 4 – Hale Road, Manchester, Connecticut

The fourth case study was Hale Road located in Manchester, Connecticut where shopping centers begin to thrive. Hale Road (Figure 10) had five intersections, providing access to chain stores, as well as access roads for further positioned stores and hotels. Hale Road has a total length of 3075 feet (0.58 miles).

Figure 10. Hale Road, Manchester, Connecticut



4.1.2. Development & Calibration of Analytical and Simulation-Based Tools

In order to evaluate the likely benefits of designing and implementing "special" signal timing plans for inclement weather conditions, two tools were required: (1) a tool for developing optimal timing plans; and (2) a microscopic simulation model for accurately assessing the impact of implementing these optimal plans. In this study, the traffic simulation models used are TRANSYT-7F, SYNCHRO, CORSIM and SIMTRAFFIC. As previously mentioned, TRANSYT-7F and SYNCHRO are signal optimization software which incorporate macroscopic simulation models of traffic flow. TRANSYT-7F and SYNCHRO are used here for the purpose of developing optimal timing plans. CORSIM and SimTraffic, on the other hand, are microscopic simulation models, and are used for more detailed evaluation of the developed signal plans. The following section gives a brief overview of these four simulation modeling tools and describes the details of their development and calibration.

4.1.2.1. A Brief Overview

TRANSYT-7F: TRANSYT is a macroscopic optimization and simulation tool originally developed in the United Kingdom by the Transport and Road Research Laboratory (TRRL). TRANSYT-7F is the United States version of TRANSYT developed by the University of Florida. TRANSYT-7F is one of the most popular signal optimization programs in the United States. The model is designed to find the set of timing parameters (i.e. phase intervals, cycle lengths, and offsets) that minimize a given performance measure (Transportation Research Center, 1998). TRANSYT-7F combines a simulation engine with an optimization routine. The simulation engine is a deterministic, *macroscopic* model that simulates traffic flow in a stepwise fashion, and hence lacks many of the details of the more refined microscopic simulation models such as CORSIM and SimTraffic. For optimization, TRANSYT-7F historically used a special application of the hill-climbing search routine, which is an iterative, gradient search algorithm. In more recent versions of the model, Genetic Algorithms (GA) optimization has been added to allow the search routine to escape from local optima.

One of the advantages of the TRANSYT-7F model is that it allows the user to select from a variety of objective functions to be used for optimization. The different objective functions available for use include functions designed to minimize delay, minimize a combination of delay and stops (the Disutility Index – DI), maximize progression opportunities (PROS), and maximize throughput (Thru) among others. The version used in this study was version 9.7, which includes a number of additional features over previous releases of the program. Among these new features are:

1. A routine for thorough cycle length optimization (CYCOPT);
2. A revised methodology for modeling traffic-actuated controllers (T7FACT);
3. A Genetic Algorithm (GA) routine to augment the traditional hill-climbing algorithm; and
4. A user-friendly graphical interface.

SYNCHRO: Similar to TRANSYT-7F, SYNCHRO, developed by Trafficware Inc., is a software package that can model and optimize traffic signal timings. SYNCHRO's simulation engine is also a macroscopic model that considers the characteristics of a traffic stream, and not individual vehicles. The version of SYNCHRO being used for this study is 5.0. Unlike TRANSYT-7F, SYNCHRO does not use the GA for optimization of signal timings. For optimization, SYNCHRO minimizes the percentile delay during optimization. The Percentile Delay is a weighted average of the delay corresponding to the 10th, 30th, 50th, 70th and 90th percentile volumes. Also, SYNCHRO uses quasi-exhaustive search in its offset optimization (Kamarajugadda *et al.* 2003; Trafficware Corporation, 1993 – 2001). Further, SYNCHRO has preprocessor features, which allows SYNCHRO files to be exported into CORSIM and TRANSYT-7F extension files. Among the new features in this version of SYNCHRO being used are the capabilities of modeling unsignalized intersections and providing information for intersection level of service.

CORSIM: CORSIM is a detailed *microscopic* model designed for the analysis of freeways, urban streets and corridors of networks (ITT Systems & Sciences Corporation, 1998). The version of CORSIM used for this study was the most recent version, 5.0. The program is capable of simulating different types of intersection controls (e.g. pretimed, actuated and coordinated traffic signals), various street geometries including lane drops and turning pockets, and a wide range of traffic flow conditions. The Federal Highway Administration developed the initial version of CORSIM in the early 1970s, and has been updating it since then. CORSIM is currently one of the most widely accepted traffic simulation models in the United States. Being a microscopic model, CORSIM uses "car following" logic to simulate the interaction of vehicles within a platoon.

SimTraffic: The SimTraffic model is a microscopic traffic simulation computer software program that can be used in conjunction with the SYNCHRO signal optimization package. SimTraffic incorporates the vehicle and driver performance characteristics developed by the Federal Highway Administration for use in traffic modeling. The underlying formulas represent over 20 years of research into traffic modeling (Trafficware Corporation, 1993–2001). The version of SimTraffic being used in this study is version 5.0. Like CORSIM, SimTraffic is capable of simulating different types of intersection controls, various street geometries including lane drops and turning pockets, and a wide range of traffic flow conditions. SimTraffic also uses "car following" logic for simulation.

4.1.2.2. Data Collection for Model Development

To assess the feasibility and benefits of implementing "special" plans for inclement weather, data was needed for developing and calibrating the traffic simulation models chosen. Data was collected for traffic conditions prevailing during the PM peak period (between 4:00 and 5:00 p.m). Several data items were needed in order to develop and calibrate the models, including:

Traffic Flow Data: This included 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 ten signal cycles were computed.

Saturation Headway and Startup Lost Time: Saturation headways and startup lost times were collected from the project site and used in developing and calibrating the simulation models for the "*dry*" weather condition.

4.1.2.3. Data Collection for Model Calibration
In addition to the above mentioned data collected, additional data items were needed for the purposes of calibrating the models. Calibration was performed by, comparing the model outputs to a number of field collected performance measures. The performance measures used for comparing the simulation model results to real world observations were:

Total Travel Time: The total travel time for the whole segment of the corridor modeled was determined by driving from one end of the corridor to the other for both the NB and SB directions. In all 7 runs were performed. The collected data was within one standard deviation of the mean total travel time.

Maximum Queue Length (MQL): The maximum queue length is the number of vehicles waiting for the GREEN signal at a signalized intersection. This excludes vehicles joining the queue after the GREEN light is activated. This data was collected over a total of 10 cycles for a sample of the corridor's signalized intersections. The MQL performance measure was used in validating the *microscopic* traffic simulation model results.

Average Maximum Back of the Queue (AMBQ): This is the measure that the macroscopic traffic simulation models uses to measure queue lengths. AMBQ gives the average maximum extension of the queue upstream on the link during the cycle. The value is considered an average, because macroscopic traffic simulation modeling involves are deterministic simulation process. As a result, approximately half of the real-world queues are expected to be higher than the average value, and the other half lower (this is different from the way the maximum queue length is defined in microscopic traffic simulation models). In addition, the maximum back of queue reported by macroscopic models includes vehicles that arrive during the green and join the back of queue, while the front of the queue is discharging during the initial seconds of the effective green. The AMBQ was determined from field observations and was used in validating the macroscopic traffic simulation models results.

4.1.2.4. Base or "Dry" Condition Model Development and Calibration
With the analysis tools selected, the next step was to develop and calibrate four models, for the existing, "dry" weather condition for each of the four corridors, using TRANSYT-7F, SYNCHRO, CORSIM and SimTraffic (i.e. a total of 16 models for just the base or dry condition). Calibration was then performed, by adjusting each model's parameters in order to bring the model's output closer to field observations. The model parameters that were adjusted during calibration are shown in Table 15 below.

Table 15. Parameters Adjusted During Calibration of Simulation Models

	CORSIM	SimTraffic	TRANYST-7F	SYNCHRO
Saturation Headway	x			
Saturation Flow rate			X	x
Startup Lost Time	x	x	X	x
Free Flow Speed	x	x	X	x
Headway Factor		x		

CORSIM Calibration: As shown in table 15 above, for CORSIM, the model's parameters that were adjusted during the calibration process included the queue discharge headway, the startup lost time, and the free flow speed. As previously mentioned, saturation headways, startup lost times and speed data were collected from the field, and the values obtained were used as a starting point for the calibration process. For checking the accuracy of the model's results, two performance measures were used: (1) the total travel time for the segment modeled, and (2) the maximum queue length (MQL).

Multiple runs of the CORSIM model were performed using different random seed numbers. The random seed numbers were created automatically using CORSEED, a utility program developed by the Advanced Traffic Analysis Center (ATAC) at North Dakota State University to allow users to generate multiple TRF files with unique seed values. In all, ten simulation runs were performed using ten differently generated random seed numbers, and the results were averaged over those ten simulation runs. For the field data, the total travel time was the average of seven car runs, that is driving from one end of the corridor to the other end, points B or A. Also the MQL was determined by considering ten cycles, as previously mentioned. The calibration parameters had to be slightly altered a number of times before the model agreed with reality. The speed was the parameter altered most as compared to the other parameters, because it had a more significant impact on the calibration results. The procedure followed was, initially a parameter (for e.g. speed) was adjusted and the simulation was run and the results were analyzed. These results were then compared to the field collected data and if large differences existed, alteration was performed again on the parameters and the simulation process was repeated. The process was continued until the results were considered reasonable and acceptable.

Table 16 below presents the calibration results obtained for Dorset Street, which compares the segment's total travel time determined from the model's output to the field-determined value. As shown, the model's results are in close agreement with field observations.

Table 16. Comparing Total Travel Time for Field-Collected Data and CORSIM

NB Direction	Travel Time/seconds	SB Direction	Travel Time/seconds
2—1	48.0	**1--2**	22.6
3—2	28.4	**2--3**	31.2
4—3	16.3	**3--4**	7.8
5—4	15.1	**4--5**	21.0
6--5	33.5	**5--6**	12.7
7--6	0.0	**6--7**	0.0
8--7	29.4	**7--8**	45.4
9--8	19.6	**8--9**	20.6
10--9	31.5	**9--10**	54.1
Total Travel Time/CORSIM	**221.8 sec.**		**215.4sec.**
Total Travel Time/Field Data	**207.0 sec.**		**213.0 sec.**
% Difference	**+ 7.2 %**		**+1.1%**

TRANSYT-7F Calibration: The TRANSYT-7F model was also calibrated for the existing "*dry*" condition using the same procedure followed in calibrating CORSIM. Table 17 below presents the calibration results obtained for Dorset Street, and compares the segment's total travel time determined from TRANSYT-7F's output against the field-measured values. As can be seen, while the travel times for the SB direction are in close agreement, those for the NB direction are not. The difference between the modeled and measured values for the NB direction is mainly due to the significantly long time given by TRANSYT-7F for traversing links (2-1) and (3-2). A closer inspection of TRANSYT-7F's output revealed that those two links were experiencing spillback conditions, which may suggest that TRANSYT-7F is overestimating travel times for oversaturated links. Comparing Tables 16 and 17, it can be seen that CORSIM results are closer to field measurements than TRANSYT-7F, which is to be expected since CORSIM, being a microscopic model, is more capable of capturing traffic dynamics.

Table 17. Comparing Total Travel Time for Field-collected Data and TRANSYT-7F

NB Direction	**Travel Time/(seconds)**	**SB Direction**	**Travel Time/(seconds)**
2—1	88.7	**1--2**	11
3—2	63.6	**2--3**	25.6
4—3	17	**3--4**	6.3
5—4	11.6	**4--5**	21.9
6—5	33.2	**5--6**	9.9
7—6	1.9	**6--7**	2
8—7	24.7	**7--8**	39.7
9—8	16.4	**8--9**	20.4
10—9	27.9	**9--10**	72.2
Total Travel Time/TRANSYT-7F	**285**		**209**
Total Travel Time/Field Data	**207**		**213**
% Difference	**+ 37.7 %**		**- 1.9 %**

4.1.3. Development of Optimal Signal Plans for Inclement Weather Conditions

4.1.3.1. Weather-Specific Models Development

With the models for the base or dry weather condition developed and calibrated, the next step was to develop similar models for traffic operations under inclement weather conditions. In this study, we modeled the following six different weather/road surface conditions as defined by FHWA: (1) dry; (2) wet; (3) wet and snowy; (4) wet and slushy; (5) slushy in wheel paths; and (6) snowy and sticky conditions. To develop the weather-specific models for each corridor, the saturation flow rate corresponding to each weather/road surface condition was coded using the reduction factors previously established in Chapter three, which gave the percent reduction relative to the "*dry*" condition rate. It should be noted, however, that we used the adjustment factors established from the data collected for the winter season of 2002-2003, since this was the only data available prior to the beginning of modeling. The free flow speeds were also reduced based upon reduction factors obtained from a previous study that assessed the impact of inclement weather on traffic flow in Salt Lake City, Utah (Perrin et al., 2001). Table 18 below summarizes the saturation flow rate and speed reduction factors used in this study. In all, six different weather-specific models were developed for each corridor, using the four different simulation models (TRANSYT-7F, SYHCHRO, CORSIM and SimTraffic), for a total of 96 models (4 corridors x 6 weather conditions x 4 different traffic simulation tools).

Table 18. Saturation Flow Rate and Free Flow Speed Reduction Factors

Weather/road surface Condition	% Reduction in Sat. Flow Rate	% Reduction in Free flow Speed
Dry	0%	0%
Wet	2%	10%
Wet & Snowy	4%	13%
Wet & Slushy	15%	25%
Slushy in Wheel Paths	21%	30%
Snowy & Sticky	16%	35%

4.1.3.2. Developing Optimal Signal Timing Plans

For a fair assessment of the likely operational benefits of developing “special” timing plans for inclement weather, the performance of these weather-specific optimal timing plans had to be contrasted against the performance of the optimal plan developed for the “dry” condition, and not just against the existing signal plan, which could be far from the optimal. Given this, 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, since it allows the model to escape out of local optima. For the GA, the crossover rate was set to 30%, and the mutation rate was equal to 1%. 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 SYNCHRO users’ manual were followed. First, the individual intersection cycle lengths were optimized followed by an 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.

4.1.4. Assessing the Likely Benefits of the “Special” Signal Plans

4.1.4.1. Choosing Performance Measures

In order to assess the likely benefits of the special timing plans, a set of performance measures for quantifying traffic flow conditions needed to be selected for each of the four models used in this study. It should be noted that some discrepancies exist between the way some of these measures are defined in the various macroscopic and microscopic simulation results (Park *et al.*, 2001). This should be kept into consideration when comparing results from the different models. Table 19 lists the different performance measures that were chosen for each model. A brief description of these measures follows. This discussion is based on how the traffic simulation models define each of these parameters and how the definitions interrelate.

Table 19. List of Performance Measures used for Benefit Assessment

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

Control Delay/Signal Delay: The Highway Capacity Manual defines control delay as the portion of the total delay attributed to traffic signal operation for signalized intersections. Control delay includes initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay. This definition is similar to the definitions from CORSIM, TRANSYT-7F and SYNCHRO references' manuals. In SYNCHRO, the signal delay is the same as the control delay. The measuring units used for this study are seconds per vehicle and minutes per vehicle.

Average Delay time: The average delay time is obtained by dividing the total delay by the number of vehicles or vehicle miles. The total delay is the difference between the total travel time and the time it would take the vehicle to travel along the corridor with no hindrance from other vehicles or traffic control devices whiles traveling at the free flow speed. This definition holds for both CORSIM and SimTraffic. If one or more links are congested, SimTraffic delays can get quite large. Each model makes different assumptions about what happens during congestion. This makes it difficult to compare delays for congested movements (Trafficware Corporation, 1993–2001). Again with CORSIM and SimTraffic the procedure used for calculating the vehicle trips seems to have an effect on the values of the delay time computed (Trafficware Corporation, 1993-2001). In CORSIM the number of vehicles is equivalent to the number of vehicles that have been discharged from the link since the beginning of the simulation (ITT Systems & Sciences Corporation, 1998). The units of measurements for the average delay time are minutes per vehicle.

Total Travel Time: It is the total time spent on the links plus the delay time. For only SimTraffic, it includes the time spent by vehicles denied entry into the travel area (link). The units of measurements used for this study are hours or vehicle hours, which are the same.

Average Speed: It is the total distance divided by the total travel time. This holds for all the different models. The average speed is either measured in miles per hour or kilometers per hour.

Total Stops: Total stops, is the total number of vehicles stopped at a traffic light and awaiting to move through the intersection. The TRANSYT-7F and SYNCHRO models in computing this parameter assumes that vehicles which are stopped, and in a queue are also delayed. The unit of measurement is number of stops per hour.

Fuel Consumption: Fuel consumption computation is based on linear combinations of total travel, delay, and stops (Trafficware Corporation, 1993–2001). The definition is applicable to both TRANSYT-7F and SYNCHRO models. The unit of measurement is in miles per gallon.

4.1.4.2. Evaluating the Benefits

To assess the benefits from the special timing plans for each weather/road surface condition, travel conditions were first quantified, using the aforementioned performance measures, under the optimal timing plan developed specifically for that particular weather condition (i.e. the weather-specific plan). These conditions were then compared to conditions obtained under the "dry" condition optimal plan (i.e. assuming that the optimal plan developed for dry condition would remain unchanged, *although the traffic flow parameters such as saturation flow rate and speed had changed because of inclement weather*). The percentage gain in the different performance measures, resulting from implementing the weather-specific optimal plans compared to the "dry" optimal plan, were then computed for each weather condition. The calculations were performed utilizing first the deterministic, macroscopic models used within TRANSYT-7F and SYNCHRO. Next, the TRANSYT-developed optimal plans were exported to CORSIM and the SYNCHRO-developed plans to SimTraffic, and the evaluation was conducted using the more detailed stochastic, microscopic models of CORSIM and SimTraffic. For CORSIM and SimTraffic, five runs with different random seed numbers were performed for each case analyzed to account for the stochastic nature of the driving environment. The same random numbers were used across the different weather conditions.

4.2. Results and Discussion

4.2.1. Results from Macroscopic Models

The benefits obtained from the macroscopic traffic simulation models (TRANSYT-7F and SYNCHRO) for the four case studies are presented below in Tables 20 through 27. These tables compare travel conditions under the "dry" optimal plan (i.e. assuming special plans are not implemented) to conditions under the weather-specific optimal plan. The tables then compute the percent benefits or gains for five different performance measures, control/signal delay, number of stops, average system speed, total travel time, and fuel consumption. In presenting these results, results for TRANSYT-7F are presented first followed by the results from the SYNCHRO model for each corridor or case study. The order of presentation for the four case studies is as follows: (1) Dorset Street in South Burlington; (2) Vermont Route 15 in Chittenden County; (3) Storrs Road in Storrs, Connecticut; and (4) Hale Road in Manchester, Connecticut.

Table 20. Special Timing Plans' Benefits – TRANSYT-7F Results for Dorset Street

Weather Condition		Control Delay (sec/veh)	Total Stops veh/hr	System Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	14.8	11412	18.7	228	306
	Weather-Specific Optimal Plan	14.4	11308	18.9	225	302
	% Gain	**2.7%**	**0.9%**	**1.1%**	**1.3%**	**1.3%**
Wet & Snowy	Under Dry Optimal Plan	15.5	11678	18.2	235	309
	Weather-Specific Optimal Plan	15.1	11527	18.4	232	307
	% Gain	**2.6%**	**1.3%**	**1.1%**	**1.3**	**0.6%**
Wet & Slushy	Under Dry Optimal Plan	18.2	12690	15.6	274	320
	Weather-Specific Optimal Plan	17.1	12225	16	267	314
	% Gain	**6.0%**	**3.7%**	**2.6%**	**2.6**	**1.9%**
Slushy in Wheel paths	Under Dry Optimal Plan	21.7	13611	13.9	309	337
	Weather-Specific Optimal Plan	18.9	12409	14.8	289	322
	% Gain	**12.9%**	**8.8%**	**6.5%**	**6.5**	**4.5%**
Snowy & Sticky	Under Dry Optimal Plan	19.6	13357	13.8	309	328
	Weather-Specific Optimal Plan	17.7	12581	14.4	297	318
	% Gain	**9.7%**	**5.8%**	**4.3%**	**3.9**	**3.0%**

Table 21. Special Timing Plans' Benefits – SYNCHRO Results for Dorset Street

Weather Conditions		Signal Delay (s/veh)	Total Stops (veh/hr)	Average Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	9	10171	24	241	340
	Weather-Specific Optimal Plan	9	9865	24	241	338
	% Gain	**0.0%**	**3.0%**	**0.0%**	**0.0%**	**0.6%**
Wet & Snowy	Under Dry Optimal Plan	9	10356	23	250	343
	Weather-Specific Optimal Plan	9	9853	24	249	339
	% Gain	**0.0%**	**4.9%**	**4.3%**	**0.4%**	**1.2%**
Wet & Slushy	Under Dry Optimal Plan	13	11856	20	300	368
	Weather-Specific Optimal Plan	11	10867	20	290	356
	% Gain	**15.4%**	**8.3%**	**0.0%**	**3.3%**	**3.3%**
Slushy in Wheel paths	Under Dry Optimal Plan	16	12905	17	389	389
	Weather-Specific Optimal Plan	13	11106	18	322	370
	% Gain	**18.8%**	**13.9%**	**5.9%**	**17.2%**	**4.9%**
Snowy & Sticky	Under Dry Optimal Plan	14	12363	17	344	379
	Weather-Specific Optimal Plan	12	10672	18	332	365
	% Gain	**14.3%**	**13.7%**	**5.9%**	**3.5%**	**3.7%**

Table 22. Special Timing Plans' Benefits – TRANSYT-7F Results for Vermont Route 15

Weather Condition		Control Delay (sec/veh)	Total Stops (veh/hr)	System Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	19.7	23491	21.2	529	706
	Weather-Specific Optimal Plan	18.4	22812	21.7	517	693
	% Gain	**6.6%**	**2.9%**	**2.4%**	**2.3%**	**1.8%**
Wet & Snowy	Under Dry Optimal Plan	21.1	24126	20.4	551	717
	Weather-Specific Optimal Plan	19.3	23447	21	534	701
	% Gain	**8.5%**	**2.8%**	**2.9%**	**3.1%**	**2.2%**
Wet & Slushy	Under Dry Optimal Plan	32.9	28869	15.8	710	805
	Weather-Specific Optimal Plan	28.2	25288	16.9	665	764
	% Gain	**14.3%**	**12.4%**	**7.0**	**6.3%**	**5.1%**
Slushy in Wheel paths	Under Dry Optimal Plan	47.1	31431	13	863	899
	Weather-Specific Optimal Plan	37.5	26722	14.5	775	827
	% Gain	**20.4%**	**15.0%**	**11.5**	**10.2%**	**8.0%**
Snowy & Sticky	Under Dry Optimal Plan	37.3	30575	13.8	814	846
	Weather-Specific Optimal Plan	30.4	25973	15	748	790
	% Gain	**18.5%**	**15.1%**	**8.7**	**8.1%**	**6.6%**

Table 23. Special Timing Plans' Benefits – SYNCHRO Results for Vermont Route 15

Weather Conditions		Signal Delay (sec/ veh)	Total Stops (veh/hr)	Average Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	17	19673	22	508	686
	Weather-Specific Optimal Plan	16	18447	23	495	667
	% Gain	**5.9%**	**6.2%**	**4.5%**	**2.6%**	**2.8%**
Wet & Snowy	Under Dry Optimal Plan	19	20867	21	539	707
	Weather-Specific Optimal Plan	17	20557	22	520	691
	% Gain	**10.5%**	**1.5%**	**4.8%**	**3.5%**	**2.3%**
Wet & Slushy	Under Dry Optimal Plan	33	28815	15	728	845
	Weather-Specific Optimal Plan	26	23405	17	662	768
	% Gain	**21.2%**	**18.8%**	**13.3%**	**9.1%**	**9.1%**
Slushy in Wheel paths	Under Dry Optimal Plan	46	36001	13	883	965
	Weather-Specific Optimal Plan	35	26234	14	777	842
	% Gain	**23.9%**	**27.1%**	**7.7%**	**12.0%**	**12.7%**
Snowy & Sticky	Under Dry Optimal Plan	37	32170	14	828	885
	Weather-Specific Optimal Plan	28	23077	15	745	787
	% Gain	**24.3%**	**28.3%**	**7.1%**	**10.0%**	**11.1%**

Table 24. Special Timing Plans' Benefits - TRANSYT-7F Results for Storrs Road

Weather Condition		Control Delay (sec/veh)	Total Stops (veh/hr)	System Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	6.1	1073	21.6	30	38
	Weather-Specific Optimal Plan	6	1047	21.6	30	38
	% Gain	**1.6%**	**2.4%**	**0.0%**	**0.0%**	**0.0%**
Wet & Snowy	Under Dry Optimal Plan	6.1	1085	21.3	31	38
	Weather-Specific Optimal Plan	6.1	1059	21.3	31	38
	% Gain	**0.0%**	**2.4%**	**0.0%**	**0.0%**	**0.0%**
Wet & Slushy	Under Dry Optimal Plan	6.4	1138	19.5	33	40
	Weather-Specific Optimal Plan	6.3	1110	19.6	33	40
	% Gain	**1.6%**	**2.5%**	**0.5%**	**0.0%**	**0.0%**
Slushy in Wheel paths	Under Dry Optimal Plan	6.7	1173	18.4	35	41
	Weather-Specific Optimal Plan	6.4	1153	18.5	35	40
	% Gain	**4.5%**	**1.7%**	**0.5%**	**0.0%**	**2.4%**
Snowy & Sticky	Under Dry Optimal Plan	6.5	1161	17.8	37	41
	Weather-Specific Optimal Plan	6.3	1127	17.9	36	41
	% Gain	**3.1%**	**2.9%**	**0.6%**	**2.7%**	**0.0%**

Table 25. Special Timing Plans' Benefits – SYNCHRO Results for Storrs Road

Weather Conditions		Signal Delay (sec/ veh)	Total Stops (veh/hr)	Average Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	3	954	23	28	35
	Weather-Specific Optimal Plan	3	842	23	28	35
	% Gain	**0.0%**	**11.7%**	**0.0%**	**0.0%**	**0.0%**
Wet & Snowy	Under Dry Optimal Plan	3	998	23	29	36
	Weather-Specific Optimal Plan	3	886	23	29	35
	% Gain	**0.0%**	**11.2%**	**0.0%**	**0.0%**	**2.8%**
Wet & Slushy	Under Dry Optimal Plan	4	1139	20	33	37
	Weather-Specific Optimal Plan	4	957	20	33	37
	% Gain	**0.0%**	**16.0%**	**0.0%**	**0.0%**	**0.0%**
Slushy in Wheel paths	Under Dry Optimal Plan	4	1201	18	36	38
	Weather-Specific Optimal Plan	4	917	19	35	37
	% Gain	**0.0%**	**23.6%**	**5.6%**	**2.8%**	**2.6%**
Snowy & Sticky	Under Dry Optimal Plan	4	1211	18	37	39
	Weather-Specific Optimal Plan	4	947	18	37	38
	% Gain	**0.0%**	**21.8%**	**0.0%**	**0.0%**	**2.6%**

Table 26. Special Timing Plans' Benefits – TRANSYT-7F Results for Hale Road

Weather Condition		Control Delay (sec/veh)	Total Stops (veh/hr)	System Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	10.7	4347	17.6	67	93
	Weather-Specific Optimal Plan	10.4	4305	17.8	66	92
	% Gain	**2.8%**	**1.0%**	**1.1%**	**1.5%**	**1.1%**
Wet & Snowy	Under Dry Optimal Plan	11.2	4508	16.8	70	94
	Weather-Specific Optimal Plan	11.2	4508	16.8	70	94
	% Gain	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Wet & Slushy	Under Dry Optimal Plan	12.7	5131	15.1	78	100
	Weather-Specific Optimal Plan	12	4727	15.5	76	96
	% Gain	**5.5%**	**7.9%**	**2.6%**	**2.6%**	**4.0%**
Slushy in Wheel paths	Under Dry Optimal Plan	14.9	5530	13.7	86	105
	Weather-Specific Optimal Plan	13	4926	14.6	80	100
	% Gain	**12.8%**	**10.9%**	**6.6%**	**7.0%**	**4.8%**
Snowy & Sticky	Under Dry Optimal Plan	13.7	5436	13.8	85	103
	Weather-Specific Optimal Plan	12.6	4737	14.3	82	98
	% Gain	**8.0%**	**12.9%**	**3.6%**	**3.5%**	**4.9%**

Table 27. Special Timing Plans' Benefits – SYNCHRO Results for Hale Road

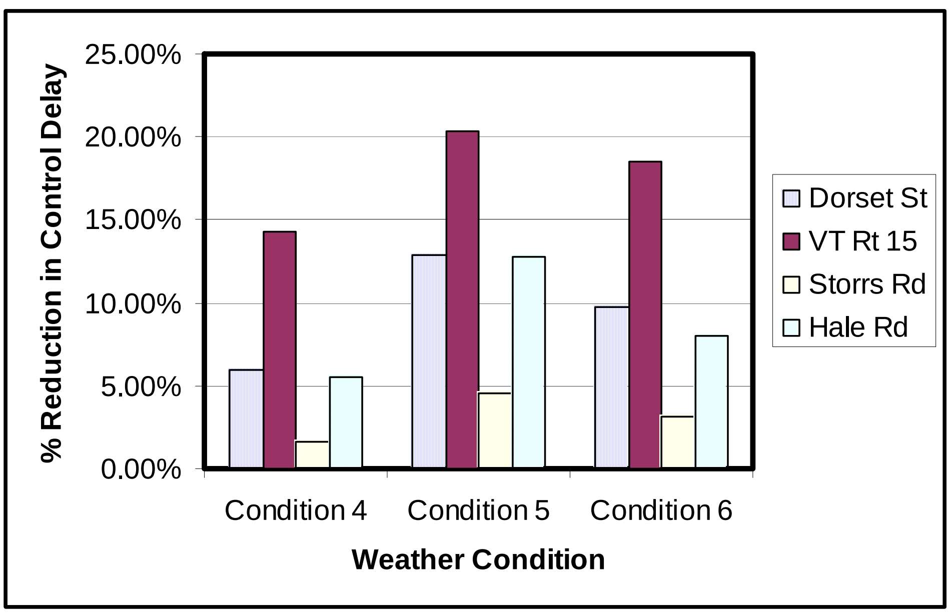
Weather Conditions		Signal Delay (sec/ veh)	Total Stops (veh/hr)	Average Speed (mph)	Total Travel Time (hrs)	Fuel Consumption (gal/hr)
Wet	Under Dry Optimal Plan	7	3394	21	54	81
	Weather-Specific Optimal Plan	7	3175	21	55	79
	% Gain	**0.0%**	**6.5%**	**0.0%**	**-1.9%**	**2.5%**
Wet & Snowy	Under Dry Optimal Plan	8	3613	20	58	82
	Weather-Specific Optimal Plan	7	3220	20	57	79
	% Gain	**12.5%**	**10.9%**	**0.0%**	**1.7%**	**3.7%**
Wet & Slushy	Under Dry Optimal Plan	11	4838	16	73	92
	Weather-Specific Optimal Plan	8	3609	17	67	82
	% Gain	**27.3%**	**25.4%**	**6.3%**	**8.2%**	**10.9%**
Slushy in Wheel paths	Under Dry Optimal Plan	13	5329	14	81	98
	Weather-Specific Optimal Plan	9	3853	16	70	84
	% Gain	**30.8%**	**27.7%**	**14.3%**	**13.6%**	**14.3%**
Snowy & Sticky	Under Dry Optimal Plan	12	5099	14	81	93
	Weather-Specific Optimal Plan	9	4094	16	73	83
	% Gain	**25.0%**	**19.7%**	**14.3%**	**9.9%**	**10.8%**

4.2.2. Discussion of Macroscopic Models' Results

Several observations can be made regarding the results shown in Tables 20 through 27. First, according to both TRANSYT-7F and SYNCHRO, the implementation of special timing plans for inclement weather appears to result, generally speaking, in significant operational benefits especially once slushy conditions start developing or once snow starts sticking to the ground. For Vermont Route 15 and for control delay, for example, TRANSYT-7F reported benefits as high as a 20% reduction, and SYNCHRO reported a 24% reduction. Second, while there are some differences between the values reported by TRANSYT-7F and SYNCHRO, the two models support the same conclusions (i.e. significant benefits especially for conditions 4 to 6).

In addition, it can be easily seen that the traffic demand and geometric characteristics of the corridor play a major role in determining the magnitude of the benefits obtained from the implementation of special timing plans for inclement weather. For example, comparing the benefits reported for Vermont Route 15 to those reported for Storrs Road, one can easily see the significant difference between the two corridors. For the control delay for the slushy in wheel path condition (condition 5), for example, the percent reductions, according to TRANSYT-7F, were 20.4% for Vermont Route 15, and only 4.5% for Storrs Road. In general, the reported benefits were highest for Vermont Route 15, followed by the benefits for Dorset Street and Hale Road (which were quite comparable to one another), and finally the benefits for Storrs Road were the lowest (see Figure 11 which compares the percent reductions in Control Delay reported by TRANSYT-7F for the four corridors and for weather conditions 4 through 6).

Figure 11. Comparing the Reported Benefits for the Four Case Studies



To try to understand some of the factors behind the differences in the reported benefits for the different corridors, the traffic and geometric characteristics of the four corridors needed to be compared. In order to quantify the traffic characteristics, we used the Intersection Capacity

Utilization (ICU) ratio, reported by the SYNCHRO model, which is a ratio of the sum of the critical movements' volumes to the saturation flow rates. The ICU ratio can, therefore, be thought of as an intersection wide volume to capacity ratio. From a geometric characteristics standpoint, the study looked at the average length of the interconnecting links between successive intersections along the corridors since this parameter plays a role in setting the *offsets* (i.e. the time difference between the moments successive signals turn green) for the signal timing plan along the corridor.

Table 28 compares the average ICU ratio and the average length of the interconnecting links for the four case studies considered. As can be seen, Vermont Route 15 intersections had the highest ICU ratio (which was significantly higher than the other three corridors), followed by Hale Road and Dorset Street intersections (which had comparable ICU ratios), and finally Storrs Road which had the lowest ICU ratio. As can be seen, there seems to be a strong link between the degree of utilization of a corridor capacity, and the magnitude of benefits to be expected from retiming the signals during inclement weather. The closer the ICU ratio to 1.0, the more significant the special timing plans' benefits are likely to be. This seems to make sense, since one would expect the reductions in saturation flow rate resulting from inclement weather to have a more significant impact on the "appropriateness" of the dry optimal plan, when one is approaching capacity.

Table 28. Traffic and Geometric Characteristics for the Four Corridors

Case Study	Number of Intersections	Average ICU Ratio (%)	Average Interconnecting Link Length (ft)
1. Dorset Street	10	56.8 %	631
2. Vermont Route 15	10	90.1 %	2112
3. Storrs Road	5	40.1 %	1107
4. Hale Road	5	60.1 %	769

From a geometric standpoint, Vermont Route 15 links had the longest average length compared to the other corridors. It therefore appears that longer interconnecting links could make the need to retime the signals during inclement weather more urgent. This also makes sense, since reductions in free flow speed during inclement weather is likely to more significantly impact the signal's coordination scheme on longer links than on shorter ones. Finally, it seems that as the number of signalized intersections along a corridor increases, the benefits of retiming signals during inclement weather increases as well.

4.2.3. Results from Microscopic Models

As previously mentioned, in addition to evaluating the benefits of the inclement weather timing plans using macroscopic simulation models, we also evaluated the plans using the more detailed, microscopic models. Specifically, the TRANSYT-developed optimal plans were exported to CORSIM and the SYNCHRO-developed plans to SimTraffic, and the evaluation was conducted using the more detailed stochastic, microscopic models of CORSIM and SimTraffic. Tables 29 through 32 summarize the results obtained from the CORSIM and SimTraffic models for Dorset Street and Vermont Route 15. For each weather condition, 20 simulation runs with different random seed numbers were made and the results were averaged in order to account for the stochastic nature of the traffic flow environment (with the same 20 seeds used across the different weather conditions cases). The duration of the simulation, for this part of the study, was set to be equal to 15 minutes. The Tables also report the gains for the following performance measures: (1) average control delay (minute/vehicle); (2) average delay (minute/vehicle); (3) total delay time (vehicle hours); and (4) average speed (mph).

As can be seen, while microscopic models still report some benefits from the implementation of special timing plans, the magnitude of the reported benefits is significantly less than those reported by the macroscopic models (i.e. TRANSYT-7F and SYNCHRO). Two reasons could be given for that. First, as mentioned above, for this part of the study, the simulation duration was only 15 minutes. As is shown later in this report, increasing the duration of the simulation (i.e. the duration of the inclement weather) results in a significant increase in the reported benefits, especially for microscopic models. For macroscopic models, the benefits are typically computed for average hourly conditions, unless a longer simulation period is requested. Second, macroscopic models are deterministic and hence the volumes used are averages that can be regarded as constant. Microscopic models, on the other hand, attempt to capture the stochastic nature of traffic, and hence inter-arrival times between vehicles vary. This could explain why the benefits obtained from microscopic models are lower than those reported by macroscopic models since in a microscopic simulation environment, while the signal plans once developed for a specific weather-condition remain unchanged, the volumes and the inter-arrival patterns do change.

In comparing the actual values of the different performance measures between macroscopic and microscopic models (Tables 20 – 23 versus Tables 29 - 32), it can be seen, that there is a reasonable agreement between the values reported for the speed and travel time (please note that for comparison, the travel time values reported by microscopic models need to be multiplied by four, since the simulation duration was only 15 minutes). For the control delay results, however, differences between macroscopic and microscopic models are quite significant. This is because the different models use different methods to compute the delay, and the assumptions used by each model are different. This could further explain why the magnitude of the benefits from the “special” timing plans estimated by the different models was different.

Table 29. Special Timing Plans' Benefits – CORSIM Results for Dorset Street

Weather Condition		Control Delay (min/veh)	Avg. Delay time (min/veh)	Total Travel Time (veh-hrs)	Avg. Speed (mph)
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
	% Gain	**2.2%**	**1.8%**	**0.3%**	**0.4%**
Wet & 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
	% Gain	**2.6%**	**1.5%**	**0.2%**	**0.4%**
Wet & 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
	% Gain	**4.1%**	**3.0%**	**0.4%**	**0.7%**
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
	% Gain	**-1.9%**	**-0.4%**	**-0.7%**	**-0.2%**
Snowy & 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
	% Gain	**-5.3%**	**-3.3%**	**-6.1%**	**-0.8%**

Table 30. Special Timing Plans' Benefits – SimTraffic Results for Dorset Street

Weather Condition		Avg. Delay Time (sec/veh)	Average Speed (mph)	Total Travel Time (hrs)
Wet	Under Dry Optimal Plan	61.40	21.60	109.04
	Weather-Specific Optimal Plan	62.54	21.55	110.38
	% Gain	**-1.9%**	**0.2%**	**-1.2%**
Wet & Snowy	Under Dry Optimal Plan	60.76	21.05	112.53
	Weather-Specific Optimal Plan	59.53	21.15	111.75
	% Gain	**2.0%**	**-0.5**	**0.7%**
Wet & Slushy	Under Dry Optimal Plan	66.57	19.00	124.07
	Weather-Specific Optimal Plan	67.42	19.00	123.83
	% Gain	**-1.3%**	**0.0%**	**0.2%**
Slushy in Wheel paths	Under Dry Optimal Plan	69.66	17.90	130.99
	Weather-Specific Optimal Plan	72.87	17.75	132.82
	% Gain	**-4.6%**	**0.8%**	**-1.4%**
Snowy & Sticky	Under Dry Optimal Plan	68.75	16.95	137.78
	Weather-Specific Optimal Plan	69.20	16.95	137.83
	% Gain	**-0.7%**	**0.0%**	**0.0%**

Table 31. Special Timing Plans' Benefits – CORSIM Results for Vermont Route 15

Weather Condition		Control Delay (min/veh)	Avg. Delay time (min/veh)	Total Travel Time (veh-hrs)	Avg. Speed (mph)
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
	% Gain	**2.6%**	**-0.9%**	**0.8%**	**0.5%**
Wet & 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
	% Gain	**1.7%**	**-1.5%**	**-4.5%**	**0.3%**
Wet & 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
	% Gain	**4.7%**	**3.4%**	**1.2%**	**1.9%**
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
	% Gain	**10.3%**	**5.0%**	**1.9%**	**2.8%**
Snowy & 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
	% Gain	**2.0%**	**1.7%**	**0.7%**	**1.2%**

Table 32. Special Timing Plans' Benefits – SimTraffic Results for Vermont Route 15

Weather Condition		Avg. Delay Time (sec/veh)	Average Speed (mph)	Total Travel Time (hrs)
Wet	Under Dry Optimal Plan	123.47	17.20	156.85
	Weather-Specific Optimal Plan	125.60	17.15	158.51
	% Gain	**-1.7%**	**0.3%**	**-1.1%**
Wet & Snowy	Under Dry Optimal Plan	127.18	16.60	160.07
	Weather-Specific Optimal Plan	130.63	16.70	160.97
	% Gain	**-2.7%**	**-0.6%**	**-0.6%**
Wet & Slushy	Under Dry Optimal Plan	137.30	15.00	173.30
	Weather-Specific Optimal Plan	132.85	15.15	172.10
	% Gain	**3.2%**	**1.0%**	**0.7%**
Slushy in Wheel paths	Under Dry Optimal Plan	143.22	14.15	181.09
	Weather-Specific Optimal Plan	139.85	14.30	179.37
	% Gain	**2.4%**	**1.1%**	**1.0%**
Snowy & Sticky	Under Dry Optimal Plan	134.34	14.05	181.71
	Weather-Specific Optimal Plan	134.96	14.00	184.09
	% Gain	**-0.5%**	**0.4%**	**-1.3%**

4.2.4. Duration of Inclement Weather Event

To assess the impact of the duration of the inclement weather event on the benefits resulting from retiming traffic signals, the study experimented with durations of 15 minutes, 1 hour and 2 hours. Figures 12 and 13 present the results obtained for three duration levels of the inclement weather event for weather conditions 4 through 6 (i.e. wet and slushy, slushy in wheel paths, and snowy and sticky), for Dorset Street and Vermont Route 15. The figures show the change in the magnitude of the gain (i.e. reduction) in the average control delay with the increase in the duration of the inclement weather event, as reported by the CORSIM model. As can be seen, there is a significant, consistent increasing trend in operational savings for the two corridors with increasing duration of the event. For example, according to CORSIM, the benefits for Dorset Street and condition 4 increased from 4.1% for a 15-minute event to 38.4% under a 2 hour-event.

Figure 12. Impact of Inclement Weather Duration on Operational Benefits (Dorset Street)

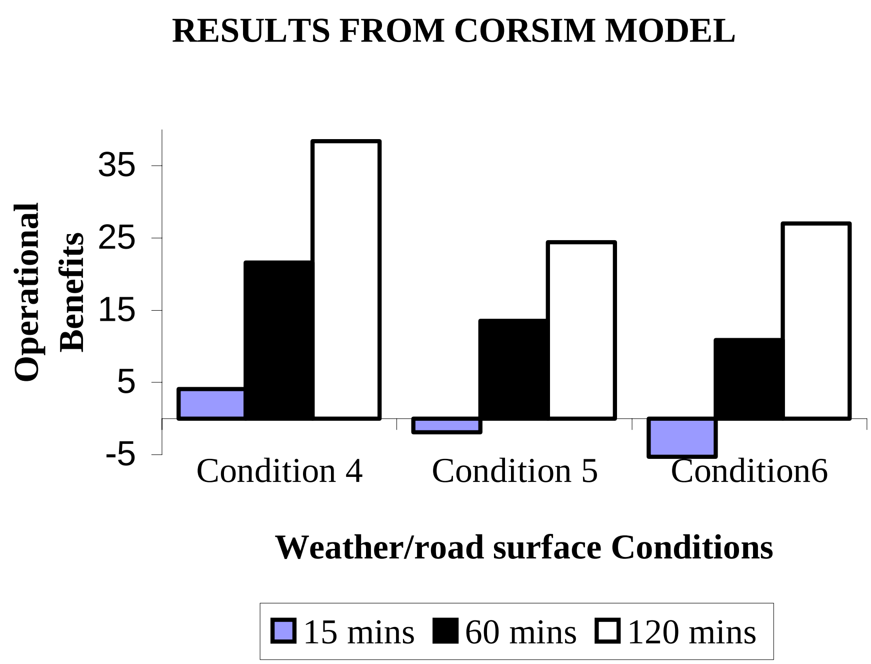
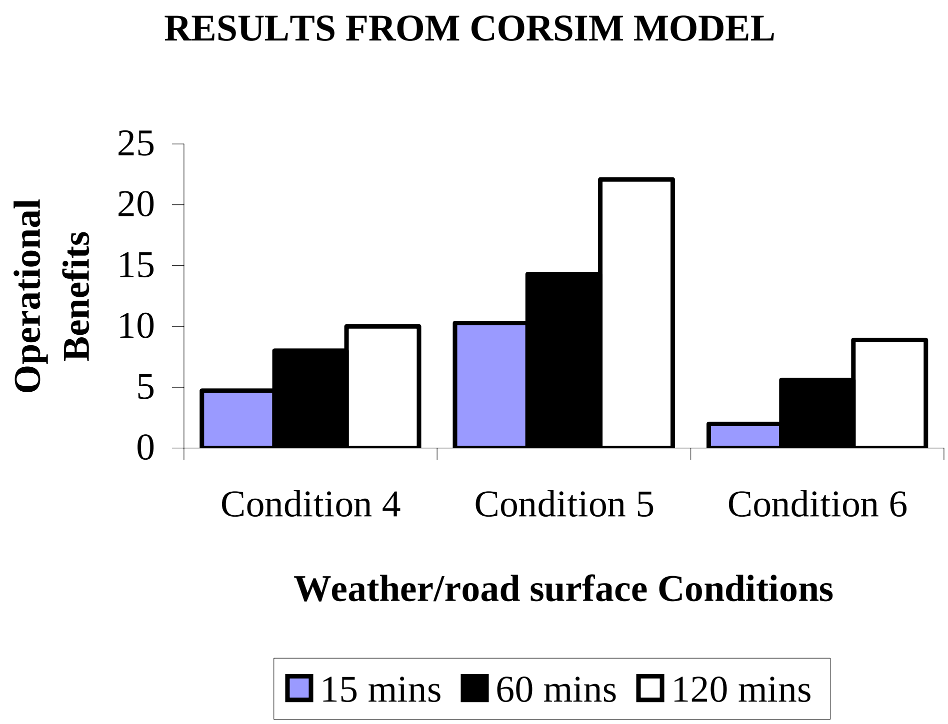


Figure 13. Impact of Inclement Weather Duration on Operational Benefits (Route 15)



CHAPTER 5 – CONCLUSIONS AND RECOMMENDATTIONS

5.1. Conclusions

This report has described a study aimed at assessing the impact of inclement weather conditions on traffic flow parameters at signalized intersections in northern New England, and on evaluating the likely operational benefits of implementing “special” timing plans for inclement weather conditions. Among the main conclusions of the study are:

1. There is enough evidence to suggest that inclement weather has a significant impact on the values of saturation headways, and hence saturation flow rates at signalized intersections;
2. The impact of inclement weather on saturation flow rates appears to be a function of the grade of the approach;
3. Out of the six different weather/road surface conditions considered in this study, conditions four through six (i.e. wet and slushy, slushy in wheel paths, and snowy and sticky) appear to have the most significant impact on saturation flow rate;
4. Values for startup lost time does not appear to be significantly impacted by inclement weather;
5. The percent reduction values in the saturation flow rate at signalized intersections obtained for New England conditions appear to closely agree with the values reported in the literature, especially for the states of Alaska and Minnesota. The values reported in the literature for Salt Lake City, Utah, however, appear to be slightly higher.
6. The implementation of special signal timing plans for inclement weather resulted in significant operational benefits for both corridors, especially once slushy conditions started developed or snow started sticking to the ground;
7. These operational benefits are a function of the traffic and geometric characteristics of the signalized corridors. The benefits tend to be more significant for corridors carrying higher traffic volumes and having longer interconnecting links between successive intersections;
8. 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
9. The duration of the inclement weather event has a significant impact on the benefits realized from inclement weather special timing plans. A significant, consistent increasing trend in operational savings can be observed for increasing durations of the inclement weather event.

5.2. Recommendations for Future Research

As can be seen from the above, the current study has clearly demonstrated the significance of studying the impact of inclement weather on traffic flow in the New England region, and the potential benefits of designing special timing plans for inclement weather. A number of future research directions are suggested by the current study

First, in this study, changes in traffic demand during inclement weather were not accounted for when devising special timing plans. As is commonly known, inclement weather typically result in a reduction in the traffic volumes observed. Given this, a study is needed to quantify these reductions, and to account for these changes in designing the weather-specific plans.

Second, this study has focused on assessing the changes in the saturation headways and start up lost times at signalized intersections in New England during inclement weather. The corresponding changes in the average speed were mainly obtained from the literature. A study is therefore needed to more accurately quantify the changes in average speeds for the different weather conditions. Changes in vehicles' accelerations and drivers' gap acceptance during inclement weather can also be quite beneficial.

Third, the fact that the benefits obtained from the microscopic traffic simulation models were lower than from the macroscopic traffic simulation models especially for short durations, suggests that the use of stochastic optimization techniques, which take into account the variations in traffic volumes, for optimal signal plan development might be a good idea. Future research should compare the benefits obtained from the use of stochastic optimization techniques versus the traditional optimization techniques used within TRANSYT-7F and SYNCHRO.

REFERENCES

Agbolosu-Amison, S. J., A. W. Sadek, and W. El-Dessouki. (2003). Inclement Weather and Traffic Flow at Signalized Intersections: A Case Study from Northern New England". In the *Journal of the Transportation Research Board (in press).*

Bernardin Lochmueller and Associates, Inc. (1995). *Anchorage Signal System Update* – Final Report.

Bretherton, D. (1996). Current Developments in SCOOT: Version 3. In *Transportation Research Record 1554,* TRB, National Research Council, Washington, D.C.

Cohen, S. L. (2004). An Approach to Calibration and Validation of Traffic Simulation Models. Presented at the *83rd Annual Transportation Research Board Meeting,* Washington, D.C.

Dowling, R., A. Skabardonis, J. Halkias, G. McHale, and G. Zammit. (2004). Guidelines for Calibration of Microsimulation Models: A Framework and Applications. Presented at the *83rd Annual Transportation Research Board Meeting,* Washington, D.C.

Federal Highway Administration (FHWA) (1997). *Economic Impact of Highway Snow and Ice Control,* Final Report. FHWA-RD-77-95.

Gilliam, W. J. and R. A. Withill. (1992). UTC and Inclement Weather Conditions, I*EE Conference Proceedings,* pp. 85 – 88.

Hanbali, R.M. (1994). Economic Impact of Winter Road Maintenance on Road Users. In *Transportation Research Record 1442*. TRB, Washington, D.C., pp. 151-161.

Head, K. L., P. B. Mirchandani, and D. Sheppard. Hierarchical Framework for Real-Time Traffic Control. In *Transportation Research Record 1360,* TRB, National Research Council, Washington, D.C. (1992).

Hellinga, B. R. *Requirements For The Calibration of Traffic Simulation Models*. CSCE (Canadian Society of Civil Engineers), University of Waterloo. 1998.

Ibrahim, A.T., and F.L. Hall. (1994). Effect of Adverse Weather Conditions on Speed-Flow-Occupancy Relationships. In *Transportation Research Record 1457,* TRB, National Research Council, Washington, D.C., pp. 184-191.

ITT Systems & Sciences Corporation. (1998). *CORSIM User's Manual.* Colorado Springs, Colorado, 1998.

Kamarajugadda, A. Park, B. (2003). *Stochastic Traffic Signal Timing Optimization.* Final report of ITS Center project, for the Center for ITS Implementation Research, U.S. DOT University Transportation Center.

Knapp, K. and L. Smithson. (2001). The Use of Mobile Video Data Collection Equipment to Investigate Winter Weather Vehicle Speeds. Presented at the *80th Annual TRB Meeting, Transportation Research Board*, National Research Council, Washington, D.C.

Liang, W.L., M. Kyte, F. Kitchener, and P. Shannon. (1998). The Effect of Environmental Factors on Driver Speed: A Case Study. In *Transportation Research Record 1635*, TRB, National Research Council, Washington, D.C., pp. 155-161.

Maki, P. J. (1999). Adverse Weather Traffic Signal Timing. *Proceedings of the 69th Annual Meeting of the Institute of Transportation Engineers*, Las Vegas, Nevada.

McShane, W., R. P. Roess, and S. E. Prassas. (2004). *Traffic Engineering*. Third Edition. Printice-Hall, Inc.

Merritt, E. (2004). Calibration and Validation of CORSIM for Swedish Road Traffic Conditions. Presented at the *83rd Annual Transportation Research Board Meeting*, Washington, D.C.

Milam, R. T. and F. Choa. (2002). Recommended Guidelines for Calibration and Validation of Traffic Simulation Models. In *Proceedings of the 8th TRB Conference on the Application of Transportation Planning Methods*, Corpus Christi, Texas, pp. 178-187.

Minitab, Inc. (2000). *Minitab On-line StatGuide, Version 13.32.* State College, PA.

Ott, L. R. and M. Longnecker. (2001). *An Introduction to Statistical Methods and Data Analysis.* 5th Edition. Wadsworth Group.

Padget, E. D; K. Knapp, and G. B. Thomas. (2001). Investigation Of Winter-Weather Speed Variability In Sport Utility Vehicles, Pickup Trucks, And Passenger Cars. In *Transportation Research Record* 1779, TRB, National Research Council, Washington, D.C., pp. 116-124.

Park, B., N. M. Rouphail, J. Hochanadel and J. Sacks. (2001). Evaluating the Reliability of TRANSYT-7F Optimization Schemes. *ASCE Journal of Transportation Engineering*, Vol. 127, No. 4, pp. 319-326

Perrin, J., P.T. Martin, and B.G. Hansen. (2001). Modifying Signal Timing During Inclement Weather. In *Transportation Research Record* 1748, TRB, National Research Council, Washington, D.C.

Rakha, H., B. Hellinga, M. Van Aerde, and W. Perez. (1996). *Systematic Verification, Validation and Calibration of Traffic Simulation Models*. Presented at the *Annual Transportation Research Board Meeting*.

Robertson, D. I. (1969). *TRANSYT: A Traffic Network Study Tool*. Road Research Laboratory, RRL report LR 253, Crowthorne, Berkshire.

Transportation Research Center. (1998). *TRANSYT-7F Users Guide*. University of Florida. Gainesville, Florida.

Trafficware Corporation. (1993 – 2001). *SYNCHRO Users Guide*. Albany CA, 94706.

Venglar, S. and T. Urbanik II. (1995). *Evolving to Real Time Adaptive Signal Control.* Proceedings of the Second Intelligent Transportation Systems World Congress, Yokohama, Japan.

Wallman, C. G., P. Wretling, and G. Oeberg. (1997). *Effects of Winter Road Maintenance – State of the Ar*t. Swedish Road and Traffic Research Institute (VTI) Sartryck, Report No. 423.