Identifying and Assessing Key Weather-Related Parameters and Their Impacts on Traffic Operations Using Simulation

PUBLICATION NO. FHWA-HRT-04-131 SEPTEMBER 2004

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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FOREWORD

Adverse weather conditions can have a dramatic impact on the quality of traffic flow. Traffic analysts need adequate traffic analysis tools to design better for the impacts of adverse weather. One available type of analysis tools is microscopic traffic simulation, which allows analysts to model and evaluate complex roadway geometries, traffic control devices, and Intelligent Transportation Systems (ITS).

The objectives of this effort, as captured in the report, *Identifying and Assessing Key Weather-Related Parameters and Their Impacts on Traffic Operations Using Simulation*, are to identify how adverse weather affects traffic operations, to assess the sensitivity of weather-related traffic parameters in a microscopic traffic simulation package (CORSIM), and to develop guidelines for using the CORSIM simulation model to account for the affects of adverse weather.

The intended audiences for this report are transportation professionals who use traffic analysis tools, in particular microscopic traffic simulation, to plan, evaluate, or design roadway or traffic control improvements and are interested in incorporating the impacts of adverse weather into their analysis.

Toni Wilbur
Director, Office of Operations Research and Development

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No. FHWA-HRT-04-131	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Identifying and Assessing Key Weather-Related Parameters and Their Impacts on Traffic Operations Using Simulation		5. Report Date September 2004 6. Performing Organization Code
7. Author(s) Li Zhang, Peter Holm, and James Colyar		8. Performing Organization Report No.
9. Performing Organization Name and Address ITT Industries Inc. Systems Division P.O. Box 15012 Colorado Springs, CO 80935-15012		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Office of Operations Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report September 2002–December 2003 14. Sponsoring Agency Code
15. Supplementary Notes The Contracting Officer's Technical Representative was John Halkias.		

16. Abstract

The objectives of this study were to identify how weather events affect traffic operations, to assess the sensitivity of weather-related traffic parameters in the CORridor SIMulation (CORSIM) traffic microsimulation model, and to develop guidelines for using the CORSIM model to account for the affects of adverse weather conditions on traffic operations.

This report summarizes the methodologies, findings, and conclusions for each of these study objectives. A high-level conclusion from this project is that CORSIM can be used adequately to model the affects of weather events on traffic operations. This conclusion is based on the fact that a majority of the generic weather-related parameters identified are currently available in CORSIM, and that the key weather-related parameters are adequately sensitive in producing model outputs inline with that expected from adverse weather.

17. Key Words traffic simulation, traffic operations, CORSIM, adverse weather, weather responsive traffic management, highway capacity		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 77	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed pages 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	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

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

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Executive Summary

Adverse weather conditions can have a dramatic impact on the operations and quality of traffic flow. With the advent of advanced traffic management systems (ATMS), there is an opportunity to develop traffic management strategies that seek to minimize negative weather-related impacts on traffic operations. Although simulation models are used widely in evaluating various traffic management strategies, applying them to evaluate ATMS strategies under adverse weather conditions needs to be explored.

The objectives of this study were to identify how weather events impact traffic operations, assess the sensitivity of weather-related traffic parameters in the CORridor SIMulation (CORSIM) traffic microsimulation model, and develop guidelines for using the CORSIM model to account for the impacts of adverse weather conditions on traffic operations.

This final report summarizes the methodologies, findings, and conclusions for each of these study objectives. A high-level conclusion from this project is that CORSIM can be used adequately to model the impacts of weather events on traffic operations. This conclusion is based on the fact that a majority of the generic weather-related parameters identified are currently available in CORSIM, and that the key weather-related parameters are adequately sensitive in producing model outputs inline with that expected from adverse weather.

This report is organized into seven major sections. A summary of each section is provided below.

Section 1—Introduction

This section presents the background and motivation for completing this project. It also highlights the objectives of the study and work tasks for each phase of the study.

Section 2—General Relationship Between Weather Events and Traffic Operations

Conceptually, it is easy to understand that a major weather event, such as a snowstorm, will lead to lower average speeds and higher delays. However, it is important to know what this relationship is, or in other words, what causes a weather event to degrade traffic operations.

This section shows that a weather event impacts traffic operations through a chain reaction: a weather event causes a change in the roadway environment (e.g., reduced visibility and pavement friction), which causes a reduction in traffic parameters (e.g., lower free-flow speeds and capacities), thereby creating a degradation in traffic flow (e.g., higher delays and lower average speeds).

The qualitative impacts of weather events are seen easily through this relationship, but the quantitative impacts have been historically difficult to measure for a number of reasons. For example, there are many “shades” of the severity of a weather event, and the impacts are different regionally (i.e., a snowstorm in Florida will have more impact than the same storm in Minnesota) and by time of year (i.e., a snowstorm at the beginning of winter will likely have more impact than the same storm near the end of winter after drivers have acclimated to the adverse weather).

Section 3—Literature Review

This section summarizes past research regarding the impact of weather events on traffic parameters, or inputs to a traffic model. Past research has shown a quantitative link between various weather events and reduced free-flow speeds, saturation (discharge) headway, startup lost time, and traffic demand.

Section 4—Identifying Simulation Parameters Affected by Weather Events

This section identifies the range of simulation parameters likely impacted by weather events. First, researchers developed a list of generic microsimulation parameters that are included in most simulation models. Then, parameters that potentially are impacted by weather events through a change in the roadway environment were determined based on the literature review and engineering judgment (e.g., adverse weather generally causes more conservative driver behavior, which means car following behavior is likely impacted by adverse weather).

Section 5—CORSIM Sensitivity Analysis

The purpose of the sensitivity study was to identify the most sensitive weather-related parameters in CORSIM. Each test parameter was modeled on various geometric networks and congestion (volume) levels using the default value and then changing the value to represent incrementally more conservative driver behavior, as would occur under adverse weather. The measures of effectiveness (MOE) produced by the default value then were compared to the MOEs produced with the changed parameter values to determine the level of sensitivity the parameter has on the MOEs.

Due to the large number of roadway networks, congestion levels, and parameters tested, approximately 45,000 individual CORSIM runs were completed. As a result, a largely automated process of creating the CORSIM input files and summarizing the output files was created specifically for this project.

One interesting result of the sensitivity analysis was that a number of parameters tested (19 total) had little or no impact on the MOEs. The majority of these were lane changing parameters. This finding does not mean they have no sensitivity whatsoever, but that they showed no sensitivity to the aggregate-level MOEs used for this study.

A number of weather-related parameters had an expected effect on the MOEs and were categorized as either having a medium or high effect on the MOEs (relative to the other parameters). These parameters are important because they represent the key weather-related parameters that should be altered when trying to model weather events in CORSIM. These parameters included the car following sensitivity multiplier and mean free-flow speed for freeway facilities , and time to react to sudden deceleration of lead vehicle, mean free-flow speed, mean discharge headway, and mean startup delay for arterial streets.

Section 6—Guidelines for Modeling Weather Events in CORSIM

This section provides practical guidelines for modeling weather events in CORSIM. The guidelines are based on *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software,* a Federal Highway Administration (FHWA) guidance document on the proper development and application of microsimulation models.[1] The guidance in this section builds on the more general microsimulation guidance by providing additional considerations when modeling weather events in CORSIM. For example, the type, severity, extent, and time period of the weather event being modeled should be agreed on before coding the model.

This section also details specific CORSIM parameters to consider changing when modeling various weather events. Finally, this section describes an alternate method of calibrating a microscopic simulation model when field data collection during adverse weather is not possible.

Section 7—Conclusions

This section summarizes the findings and results of each phase of the study and also highlights four areas of future research: empirical data collection to improve base understanding of impact of weather events on traffic operations, CORSIM enhancements for modeling adverse weather events, further study of CORSIM parameters which showed no or little sensitivity, and real-world case study of modeling weather events using CORSIM.

1. Introduction

Background

Adverse weather conditions can have a dramatic impact on the operations and quality of traffic flow. For example, icy pavement conditions can affect the acceleration and deceleration capabilities of vehicles. Reduced visibility can cause drivers to alter their desired speed, how they change lanes, and how they follow other vehicles. Major weather events can cause drivers to modify their travel patterns, such as taking a different route to a destination, leaving for a destination at a different time than normal, or canceling a trip altogether.

With the advent of ATMS, there is an opportunity to develop traffic management strategies that attempt to minimize the negative weather-related impacts on traffic operations. For instance, a weather event that reduces the average operating speed on an arterial can be mitigated by quickly implementing traffic signal plans that account for the lower speeds while still maintaining progression through a network. However, to develop and implement strategies that minimize the effects of adverse weather conditions, a more complete knowledge of how weather events affect traffic operations and how to assess the weather-related effects for a given scenario is needed.

Currently, the relationship between weather events and traffic operations is moderately understood, but only at a macroscopic analysis level, such as the methodologies presented in the *Highway Capacity Manual* (HCM).[1(2)] Using an HCM-style analysis is, in fact, one way to model weather impacts to develop weather-responsive traffic management strategies. However, a more detailed and potentially more accurate method is to use a microscopic traffic simulation model. A microscopic simulation tool can model individual vehicles on a roadway network, typically on a second-by-second basis or less. Simulation models have the benefit of being able to model complex roadway geometries, traffic control devices, and vehicle configurations that are beyond the limitations of a macroscopic HCM-style analysis.

However, modeling microscopic driver behavior is difficult under ideal weather conditions, let alone under adverse weather conditions. Little research has been conducted on how weather events impact microscopic driver behavior logic, such as lane changing and vehicle following, both of which are crucial to the accuracy of a microscopic traffic simulation model. In addition, a vast number of user-input parameters within simulation models can be altered. Knowing which key parameters within a microsimulation model should be changed under various weather conditions would aid greatly in developing weather-responsive traffic management strategies.

Study Objective

The objectives of this study are to identify how weather events impact traffic operations, assess the sensitivity of weather-related traffic parameters in the CORSIM traffic simulation model, and develop guidelines for using the CORSIM model to account for the impacts of adverse weather conditions on traffic operations. More specifically, this study is tasked to do the following:

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[1] HCM methodologies do not specifically address the impacts of weather events on highway capacity and quality of service: however, the parameters in the HCM could be user-adjusted to reflect the impacts of weather events.

- Research the relationship between weather events and traffic operations.
- Identify which types of simulation parameters could be affected by weather events.
- Conduct a sensitivity analysis on selected CORSIM simulation parameters to identify the key weather-related parameters that most affect traffic operations.
- Develop basic guidelines on how weather events can be modeled using CORSIM.

This study does not recommend specific values (e.g., free-flow speed of 70 kilometers/hour (km/h)) to be used for each parameter under various weather conditions. Rather, it focuses on identifying the general sensitivity of a parameter to traffic operation MOEs (i.e., average speed). This information then may be used to develop guidelines on how CORSIM can be used to model weather events.

Study Approach

This study, which began in September 2002, was conducted on a task order basis with a total of five tasks. Figure 1 shows a flowchart of the task breakdown and workflow. As shown in this figure, the tasks were completed in consecutive order, because the output from one task was required for the next task. This report provides the results for each of these tasks.

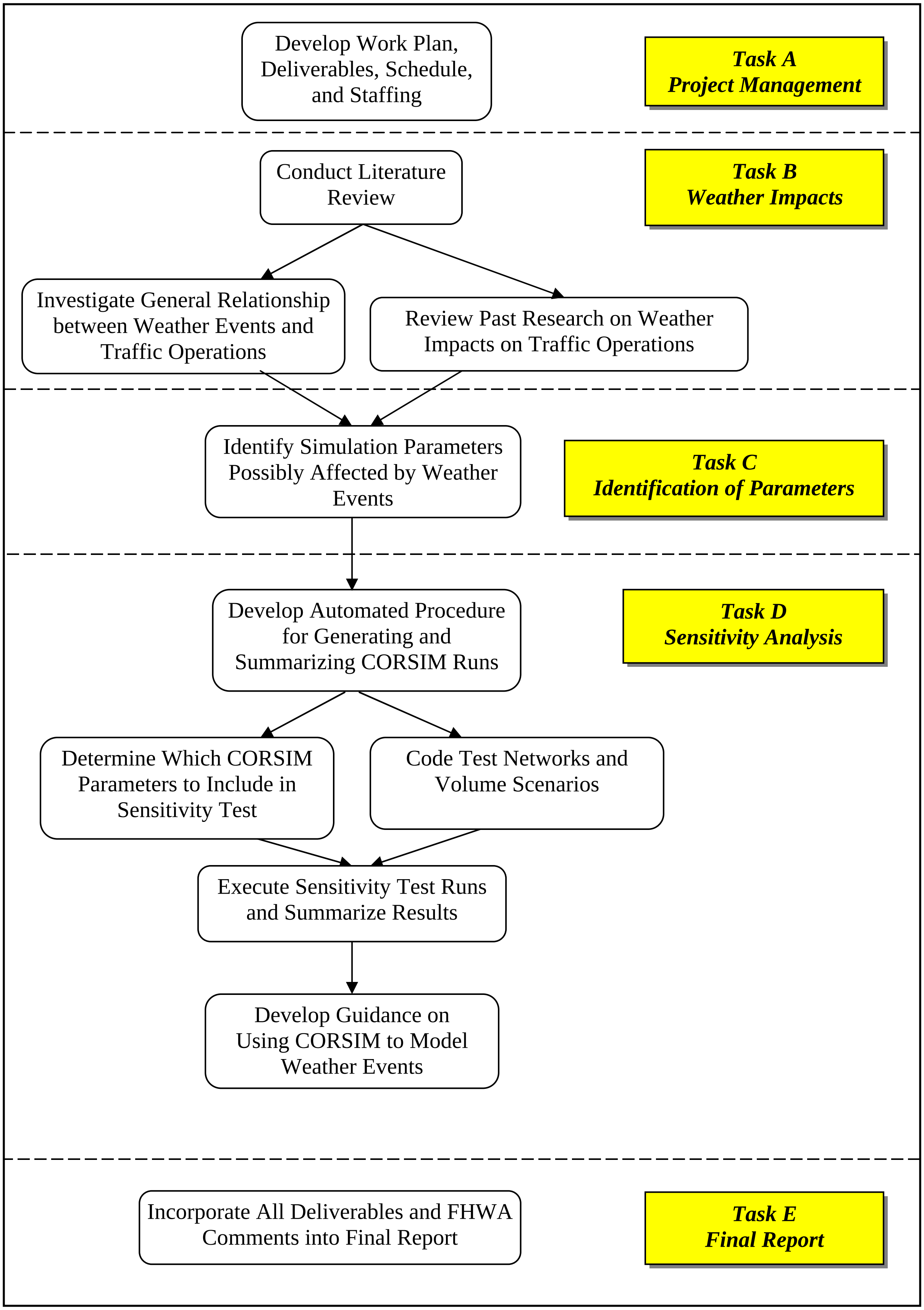


Figure 1. Study Approach.

Report Outline

This report represents the final task (Task E in figure 1) for the “Identifying and Assessing Key Weather-Related Parameters and Their Impacts on Traffic Operations Using Simulation” project. This report is separated into the following sections:

- **Section 1** discusses the objective and approach of the project, including a background discussion on the need for the study.
- **Section 2** discusses the general relationship between weather events and traffic operations, including a discussion of how a change in weather leads to a change in the quality of traffic flow.
- **Section 3** discusses the results of a literature search on field studies of the effects of adverse weather on traffic operations parameters.
- **Section 4** identifies which simulation parameters are potentially sensitive to weather events.
- **Section 5** describes the study methodology and results of the CORSIM sensitivity study of the key weather-related parameters identified in section 4.
- **Section 6** develops guidelines for modeling weather events using CORSIM.
- **Section 7** summarizes the findings and conclusions of the report and identifies future research needs.
- **Section 8** lists the report references.

2. General Relationship Between Weather Events and Traffic Operations

Conceptually, it is easy to understand that a major weather event, such as a snowstorm, will lead to lower average speeds and higher delays. However, it is important to understand what this relationship is, or in other words, what causes a weather event to degrade traffic operations.

Figure 2 shows the general relationship between weather events and the resulting impact on traffic operations. This relationship is similar to that shown by Pisano and Goodwin, with the exception that the definition of “traffic operations” has been divided into two subparts: traffic parameters (or characteristics) and quality of traffic flow.(3) Traffic parameters are quantitative values that typically are used as inputs to a traffic analysis model. These parameters account for how drivers and their vehicles interact and respond to the roadway network, including the response to other vehicles, traffic control devices, roadway geometry, weather, and other environmental conditions. The quality of traffic flow is the output from a traffic analysis model and is calculated using MOEs. MOEs measure the overall performance of the transportation system, which is directly related to how well drivers and their vehicles respond to the surrounding factors (traffic parameters). Common MOEs include average speed, average density, average delay per vehicle, and number of stops.

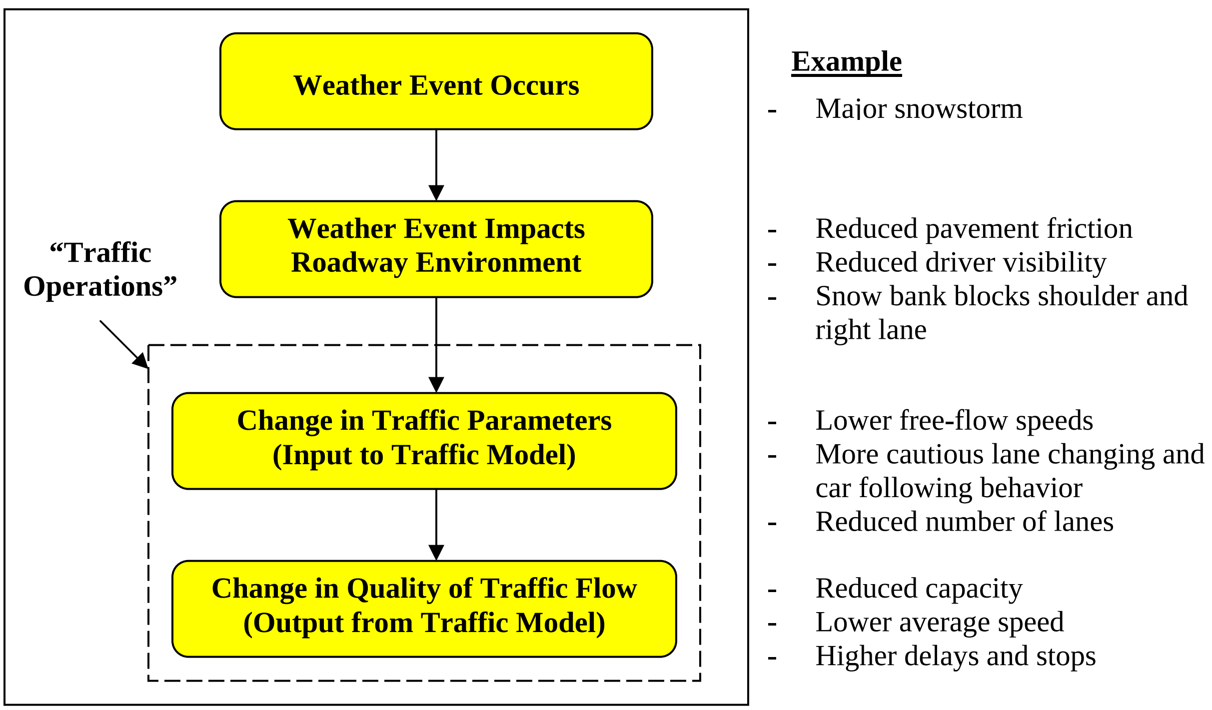


Figure 2. Relationship Between Weather Events and Traffic Operations.

This distinction between the input and output in traffic operations is important because traffic analysts need to know, for a certain weather event, which traffic parameters to change and how much to change them when inputting these parameters into a traffic analysis model. These changes will produce a new quality of traffic flow reflecting the impacts of the weather event.

Definition of Weather Event

Weather events are any meteorological occurrence that causes weather conditions to degrade from the "ideal" weather condition. The ideal weather condition is defined as having the following conditions:

- No precipitation.
- Dry roadway.
- Good visibility (greater than 0.4 km).
- Winds less than 16 km/h.[(4)]

Weather events can change quickly in severity and in coverage area. These changes over time and space present a challenge in modeling weather events in a traffic analysis model. The ranges of possible weather events that are addressed in this study include rain, snow, sleet, hail, flooding, fog, ice, sun glare, lightning, dust, wind, and extreme temperatures.

Relationship Between Roadway Environment and Weather Event

Weather events cause a change in the "roadway environment," a term used by Pisano and Goodwin, meaning a physical change in the roadway or roadway devices, or a change on the immediate environment surrounding the roadway (including the driver), and vehicle changes.[(3)] Each weather event impacts the roadway environment differently. Table 1 shows the connection between weather events and the roadway environment. As shown in the table, various weather events, such as fog, dust, rain, snow, sleet, hail, and sun glare, can reduce driver visibility.

Table 1. Impacts of Weather Events on Roadway Environment.

Weather Events	Impact on Roadway Environment
Fog, dust, rain, snow, sleet, hail, sun glare	Reduced driver visibility
Ice, rain, snow, sleet, hail, flooding	Blocked lanes or covered signs and pavement markings Reduced pavement friction (note that reducing pavement friction leads to a reduction in vehicle maneuverability)
Wind	Reduced vehicle maneuverability and stability
Extreme temperatures, lightning, wind	Failed traffic control devices and communications

Relationship Between Roadway Environment and Traffic Parameters

As the roadway environment changes, resulting changes in traffic parameters will occur. For example, a reduction in driver visibility will logically cause most drivers to drive more cautiously, to some degree. This changed driver behavior is reflected in simulation traffic parameters, such as lower free-flow speeds and more cautious lane changing and car following parameters. Traffic parameters represent values that a traffic engineer can control in a simulation model. The ability to modify these parameters in a simulation model provides the means for simulating the impacts of adverse weather conditions. The challenge with microscopic simulation models like CORSIM is that they require many more input traffic parameters than a macroscopic HCM-style model due to the complex modeling of driver behavior on an individual vehicle basis.

Before tracing which traffic parameters are impacted by a change in the roadway environment, it is important to understand the full range of parameters available in a microscopic simulation model. Table 2 displays a generic list of possible traffic parameters in a microscopic simulation model. The parameters are considered generic because they are not specific to any one model, and the majority of them are included in most simulation models currently available. However, each model uses slightly different terminology to define these parameters. Therefore, the parameters listed in table 2 may only be a subset of the actual simulation models parameters. For example, there are more than 20 parameters in CORSIM that are used to model lane changing behavior.

Tracing which traffic parameters are likely affected by weather events (through a change in the roadway environment) was performed based on a review of table 2, the literature review (section 3), and engineering judgment. The results of this analysis are presented in section 4 after the literature review section.

Table 2. Range of Generic Traffic Simulation Parameters.

Category	Parameters
Road geometry	Pavement condition (wet, dry, etc.) Number of lanes Lane width Lane taper length Segment link length Shoulder type/width Grade Horizontal and vertical curvature Super-elevation
Traffic control and management	Traffic signal - Controller type - Green splits, clearance intervals - Progression settings - Actuated settings (detectors, vehicle extension time, etc.) Ramp meter Regulatory signs (Stop, Yield, Speed Limit, etc.) Warning signs (Lane Ends, Merge Ahead, etc.) Traveler information signs (Variable Message Signs, route guidance signs, etc.) Surveillance detectors (type and location) Lane use by movement (turn only, through only, shared through-turn) Lane use by vehicle type (HOV, transit only, no trucks, etc.) On-street parking
Driver behavior	Car following Lane changing Free-flow speed Discharge headway Startup lost time Queue separation/spacing Gap acceptance at intersections Turning speed Rubbernecking (response to incidents) Response to yellow interval Illegal maneuvers
Events/scenarios	Incidents/blockages (severity, duration) Incident management (response, emergency vehicle dispatch, etc.) Work zones
Vehicle performance	Vehicle type distribution (% trucks, buses, etc.) Acceleration/deceleration capability (stopping distance) Turning radius Vehicle length
Simulation run control	Length of simulation run Selected output MOEs (reports, animation files, etc.) Resolution of simulation results (temporal and spatial resolution)
Traffic demand	Vehicle demand (including changes over time), expressed as: - Entry demands and turning percentages - Origin-destination demands Route choice
Multimodal operations	Transit operations (routes, stops, headways, dwell times, etc.) Bicycle operations (volumes, free-flow speeds, shared/exclusive paths, etc.) Pedestrian operations (volumes, walking speeds, priority rules, sidewalk characteristics, etc.)

3. Literature Review

Past research on the simulation of traffic operations under adverse weather conditions can be organized into two main groups: those focusing on the link between weather events and traffic parameters (i.e., heavy rain reduces free-flow speeds by 30 percent), and those focusing on the link between weather events and the quality of traffic flow (i.e., heavy rain increases delays by 40 percent). This review focuses on the former, because knowing the impact of weather events on traffic parameters is the key to using microsimulation to model weather events.

Very little research focusing on the roadway environment impacts shown in table 1 were found. This lack of information probably is due to the difficulty in understanding why motorists respond to a weather event (i.e., is a reduction in free-flow speed really due to a reduction in pavement friction or reduction in visibility?) The literature review yielded information on the impacts of weather events on the following traffic parameters: free-flow speed, startup lost time, saturation headway, and traffic demand.

Free-Flow Speed

A number of studies have shown that adverse weather events reduce the mean free-flow speed, which is defined as the desired speed of drivers in low volume conditions and in the absence of traffic control devices.(2) The amount of reduction in free-flow speed is directly related to the severity of the weather event. Kyte et al. studied the free-flow speed on a rural freeway during wet and snow-covered pavement, high wind (greater than 24 km/h), and low visibility conditions (less than 0.28 km).(4) They found the free-flow speed reduced by approximately:

- 10 km/h (8 percent) during wet pavement.
- 16 km/h (13 percent) during snow-covered pavement.
- 17 km/h (14 percent) during high wind.
- 18 km/h (15 percent) during low visibility.
- 35 to 45 km/h (30 to 38 percent) during a combination of snow-covered pavement, low visibility, and high wind.

May showed that the free-flow speed on freeways was reduced by approximately:(5)

- 8 percent under light rain or snow.
- 17 percent under heavy rain.
- Up to 40 percent under heavy snow.

Based on a study of two-lane rural highways, Lamm, Choueiri, and Mailaender found that drivers do not adjust their speeds very much under light rain or wet pavement, but they do reduce speeds when visibility becomes obstructed, such as during a heavy rain.(6)

On a sample of freeways in Canada, Ibrahim, and Hall also found that free-flow speed is noticeably decreased during heavy rain and snow; heavy snow (up to 50 km/h reduction) has a much greater effect than heavy rain (up to 10 km/h reduction).(7)

Perrin, Martin, and Hansen measured free-flow speed reductions at two signalized intersections on an arterial in Salt Lake City, UT of:[8]

- 10 percent on wet pavement.
- 25 percent on wet and slushy pavement.
- 30 percent on pavement with slushy wheel paths.

Other studies have shown a reduction in average speed on arterials.[9,10] Average speed, a typical MOE used by traffic engineers, is a different value than free-flow speed; average speed accounts for the effects of signal timing and other effects related to the interaction with other vehicles.

Startup Lost Time

Startup lost time is defined as the additional time consumed by the first few vehicles in a queue at a signalized intersection beyond the saturation headway.[2] This additional time is due to the time to react to the start of the green phase and for the vehicle to accelerate from a stopped position. Under ideal conditions, the HCM recommends using 2.0 seconds for startup lost time.

Maki measured an increase in startup lost time of 50 percent, from 2.0 seconds during normal conditions to 3.0 seconds under adverse weather conditions, which was defined as being a storm with accumulation of 7.6 centimeters (cm) or more of snow, on a signalized expressway in the Minneapolis/St. Paul, MN area.[9]

Perrin, Martin, and Hansen measured a startup lost time increase of approximately 25 percent, from 2.0 to 2.5 seconds, under severe snow-related conditions.[8] However, only a small difference, from 2.0 to 2.1 seconds, was measured during rain-related conditions.

Saturation Headway

Saturation headway, or discharge headway, is defined as the average headway between vehicles occurring after the fourth vehicle in a signalized intersection queue and continuing until the last vehicle in the initial queue clears the intersection.[2] Saturation headway (expressed in units of seconds/vehicle (s/veh)) is the inverse of saturation flow rate (veh/s or veh/h). For example, a 10 percent increase in saturation headway equates to a 10 percent decrease in saturation flow rate. The HCM recommends an ideal discharge headway of 1.9 seconds (equates to a saturation flow rate of 1900 passenger cars/h/lane). This value then is reduced based on adjustments for lane width, heavy vehicles, grade, adjacent parking, bus blockage, area type, lane utilization, right and left turns, pedestrians, and bicyclists.

Perrin, Martin, and Hansen measured an average reduction in saturation flow rate of between 6 and 20 percent, increasing with weather severity (snow packed on the street surface being the highest severity).[8]

Maki found a saturation flow rate reduction of approximately 10 percent, from 1800 to 1600 veh/h/lane under adverse weather conditions as defined above.[9]

Botha and Kruse measured the effect of residual ice and snow on a signalized arterial in Fairbanks, AK. Saturation flow rates were found to be approximately 20 percent lower than the ideal HCM-recommended conditions.[11]

Traffic Demand

Maki measured a reduction in traffic volumes of 15 to 30 percent during adverse weather conditions when compared to ideal weather conditions.[9] The reduction in traffic volumes was attributed to various reasons, including shifting work arrivals and departures, and avoidance of discretionary trips. Traffic demand changes depend strongly on the severity of the weather conditions and the driver's comfort in adverse weather conditions. For example, drivers in Chicago, IL will react differently to a snowstorm than will drivers in Miami, FL.

4. Identifying Simulation Parameters Affected by Weather Events

The literature review documented a number of traffic parameters that were found to be impacted by weather events. However, there are numerous other microsimulation parameters that have not been measured empirically to behave differently during adverse weather. It is important to identify these parameters and include them in the sensitivity study.

Tables 3 through 7 show the traffic simulation parameters that likely are impacted by weather events (through a change in the roadway environment). The selection of these parameters was based on the range of simulation parameters identified in table 1, the literature review, and the use of engineering judgment based on the concept that driver behavior becomes more conservative during adverse weather conditions. Unfortunately, there is currently no empirical research supporting this concept. Therefore, the table only lists the range of potential, not proven, simulation parameters that may be used to model adverse weather conditions in a simulation model. These simulation parameters may be used as a guide for traffic analysts when considering which parameters to adjust when modeling adverse weather.

The remainder of this section discusses how parameters in each major category (road geometry, traffic control and management, vehicle performance, traffic demand, and driver behavior) may be impacted by weather events.

Road Geometry Parameters

Table 3 displays road geometry parameters likely impacted by weather events though a change in the roadway environment. If available in a simulation model, the pavement condition parameter should be modified during a weather event, causing a reduction in pavement friction. The traffic analyst should be aware, however, how the pavement condition parameter affects other parameters. For example, changing the pavement condition parameter in FRESIM (the freeway model within CORSIM) causes an automatic reduction in free-flow speed for a link in a horizontal curve. Also, a weather event causing a lane or shoulder blockage would alter the number and width of available lanes, length of tapers associated with lane adds and drops, and shoulder width.

Table 3. Road Geometry Traffic Parameters Impacted by Weather Events.

Generic Traffic Simulation Parameter	Weather Events				
	Fog, Dust, Rain, Snow, Sleet, Hail, Sun Glare	Ice, Rain, Snow, Sleet, Hail, Flooding	Wind, Ice, Rain, Snow, Sleet, Hail, Flooding	Ice, Rain, Snow, Sleet, Hail, Flooding	Extreme Temperatures, Lightning, Wind
	Roadway Environment Impact				
	Reduced Visibility	Reduced Pavement Friction	Reduced Vehicle Maneuverability /Stability	Blocked Lanes/ Covered Signs and Pavement Markings	Failed Traffic Control Devices and Communications
Pavement condition		X			
Number of lanes				X	
Lane width				X	
Lane taper length				X	
Shoulder width				X	

Traffic Control and Management Parameters

Table 4 displays traffic control and management parameters likely impacted by weather events though a change in the roadway environment. A reduction in visibility would make it difficult for drivers to see traffic signals or signs. Thus, the parameters related to sight or reaction distance to the traffic signals and signs would need to be altered. Also, a weather event that caused a sign blockage would require altering the parameters related to the visibility of, and compliance with, traffic signs. Finally, a weather event causing a power failure and loss of communications between traffic devices or to a traffic management center would require altering the traffic signal settings (i.e., change to emergency flash operation), or removing the functionality of detector devices, including those used at traffic signals, ramp meters, or systemwide surveillance.

Table 4. Traffic Control and Management Parameters Impacted by Weather Events.

Generic Traffic Simulation Parameter	Weather Events				
	Fog, Dust, Rain, Snow, Sleet, Hail, Sun Glare	Ice, Rain, Snow, Sleet, Hail, Flooding	Wind, Ice, Rain, Snow, Sleet, Hail, Flooding	Ice, Rain, Snow, Sleet, Hail, Flooding	Extreme Temperatures, Lightning, Wind
	Roadway Environment Impact				
	Reduced Visibility	Reduced Pavement Friction	Reduced Vehicle Maneuverability /Stability	Blocked Lanes/ Covered Signs and Pavement Markings	Failed Traffic Control Devices and Communications
Traffic signal	X				X
Ramp meter	X				X
Regulatory signs	X			X	
Warning signs	X			X	
Traveler information signs	X			X	X
Surveillance detectors					X
On-street parking				X	

Vehicle Performance Parameters

Table 5 displays vehicle performance parameters likely impacted by weather events though a change in the roadway environment. A reduction in pavement friction could affect the acceleration and deceleration capabilities of vehicles. These parameters relate to the performance of the vehicle only, and not necessarily the behavior of the drivers. The acceleration and deceleration capability of vehicles typically are used in the car following and lane changing logic of a simulation model; therefore, changing these parameters likely will alter the way vehicles follow each other and change lanes in a model.

Table 5. Vehicle Performance Traffic Parameters Impacted by Weather Events.

Generic Traffic Simulation Parameter	Weather Events				
	Fog, Dust, Rain, Snow, Sleet, Hail, Sun Glare	Ice, Rain, Snow, Sleet, Hail, Flooding	Wind, Ice, Rain, Snow, Sleet, Hail, Flooding	Ice, Rain, Snow, Sleet, Hail, Flooding	Extreme Temperatures, Lightning, Wind
	Roadway Environment Impact				
	Reduced Visibility	Reduced Pavement Friction	Reduced Vehicle Maneuverability /Stability	Blocked Lanes/ Covered Signs and Pavement Markings	Failed Traffic Control Devices and Communications
Acceleration/ deceleration capability		X	X		
Turning radius		X	X		

Traffic Demand Parameters

Table 6 displays traffic demand parameters likely impacted by weather events through a change in the roadway environment. Any weather event causing one or more major roadway environment impacts could cause a change in vehicle demand and route choice. For example, a major snowstorm over an entire city could cause vehicle demand to be reduced on all links, whereas an isolated storm affecting only a small number of roads could result in no change in overall traffic demand but different route choices, because drivers would avoid the impacted roads. Many simulation models allow the input of traffic demands as origin-destination pairs with a traffic assignment procedure (which determines the preferred route for motorists in traveling between their origin and destination) built into the model. For these models, changing the appropriate parameters to reflect the conditions of the snowstorm on the isolated roads would allow the traffic assignment algorithm to predict automatically the change in route choice associated with the snowstorm.

Table 6. Traffic Demand Traffic Parameters Impacted by Weather Events.

Generic Traffic Simulation Parameter	Weather Events				
	Fog, Dust, Rain, Snow, Sleet, Hail, Sun Glare	Ice, Rain, Snow, Sleet, Hail, Flooding	Wind, Ice, Rain, Snow, Sleet, Hail, Flooding	Ice, Rain, Snow, Sleet, Hail, Flooding	Extreme Temperatures, Lightning, Wind
	Roadway Environment Impact				
	Reduced Visibility	Reduced Pavement Friction	Reduced Vehicle Maneuverability /Stability	Blocked Lanes/ Covered Signs and Pavement Markings	Failed Traffic Control Devices and Communications
Vehicle demand	X	X	X	X	X
Route choice	X	X	X	X	X

Driver Behavior Parameters

Table 7 displays driver behavior parameters likely impacted by weather events though a change in the roadway environment. Many driver behavior parameters are impacted by weather events causing visibility, pavement friction, or vehicle maneuverability reductions. Car following and lane changing behavior likely will be more cautious during weather events, with the degree of caution dependent on the severity of the weather event. Free-flow speed, startup lost time, and discharge headway all have been documented to degrade during weather events. In addition, intersection-related parameters such as gap acceptance, turning speed, and responses to the yellow interval likely are impacted by weather events.

Table 7. Driver Behavior Traffic Parameters Impacted by Weather Events.

Generic Traffic Simulation Parameter	**Weather Events**				
	Fog, Dust, Rain, Snow, Sleet, Hail, Sun Glare	Ice, Rain, Snow, Sleet, Hail, Flooding	Wind, Ice, Rain, Snow, Sleet, Hail, Flooding	Ice, Rain, Snow, Sleet, Hail, Flooding	Extreme Temperatures, Lightning, Wind
	Roadway Environment Impact				
	Reduced Visibility	Reduced Pavement Friction	Reduced Vehicle Maneuverability /Stability	Blocked Lanes/ Covered Signs and Pavement Markings	Failed Traffic Control Devices and Communications
Car following	X	X	X	X	
Lane changing	X	X	X	X	
Free-flow speed	X	X	X	X	
Discharge headway	X	X	X	X	
Startup lost time	X	X	X	X	
Intersection gap acceptance	X	X	X	X	
Turning speed	X	X	X	X	
Response to yellow interval	X	X	X	X	

5. CORSIM Sensitivity Analysis

The purpose of the sensitivity analysis was to determine which weather-related traffic parameters have the greatest impact on the quality of traffic flow. It was necessary to identify the most sensitive weather-related parameters to develop the guidelines for using CORSIM in modeling adverse weather conditions.

The sensitivity study showed how these parameters impacted the quality of traffic flow. Various geometric configurations and congestion levels were tested to get a complete assessment of the overall sensitivity of a parameter.

The sensitivity study started with a baseline case created using the default values for the parameters. The sensitivity study focused on changing one parameter value at a time, regenerating the MOEs, and comparing the new MOEs to the baseline case.

This method was found to be limiting, but within the scope of this project. A potentially more detailed and realistic sensitivity test would be to change multiple parameter values at once, to model specific weather events. This method was not within the scope of the project and would result in exponentially increased data processing and analysis efforts. It should be considered for future sensitivity testing efforts.

The sensitivity study was divided into two major groups: sensitivity of parameters on freeway facilities using Freeway Simulation (FRESIM), which is the simulator within CORSIM that models all freeway facilities; and sensitivity of parameters on arterial streets using Network Simulation (NETSIM), which is the simulator within CORSIM that models all arterial and local streets.

FRESIM Analysis Methodology

A number of different geometric scenarios, or networks, were developed to test the sensitivity of the parameters under various roadway configurations using the FRESIM model in CORSIM. For example, a parameter may not show any sensitivity on a basic freeway segment, but show high sensitivity on a short weaving area. The networks developed for the FRESIM sensitivity analysis are shown in table 8.

All networks were assumed to have ideal conditions as defined in the HCM, including 3.65-m travel lanes, level grade, no horizontal curves, and no heavy trucks.(2) All freeway segments were assumed to have a free-flow speed of 113 km/h, while all on- and off-ramps were assumed to have a free-flow speed of 72 km/h. Also, an analysis period of one hour was used for all simulation runs.

Table 8. FRESIM Sensitivity Analysis Networks.

Network Name	Description
One-lane basic segment	One-lane freeway with no on- or off-ramps, 1.6 km long.
Two-lane basic segment	Same as the one-lane basic segment, except with two freeway lanes.
Three-lane basic segment	Same as the one-lane basic segment, except with three freeway lanes.
Two-lane merge area	Two-lane freeway with a single on-ramp, with a ramp volume of 500 veh/h and 230 m acceleration lane.
Three-lane merge area	Same as the two-lane merge area, except with three freeway lanes.
Two-lane diverge area	Two-lane freeway with a single off-ramp, with an exiting ramp volume of between 300 and 750 veh/h (fixed at 15% of freeway volume) and 230 m deceleration lane.
Three-lane diverge area	Same as the two-lane diverge area, except with three freeway lanes.
Two-lane weave area	Two-lane freeway with an on-ramp and off-ramp separated by 300 m, on-ramp volume of 500 veh/h, off-ramp volume of between 375 and 825 veh/h (fixed at 15% of freeway volume), and single auxiliary lane connecting the on- and off-ramps.
Three-lane weave area	Same as the two-lane weave area, except with three freeway lanes.
System	5.15-m, three-lane freeway system including two merge areas (each with 150-m acceleration lanes), one diverge area (with a 150-m deceleration lane), and one weave area (with a 300-m auxiliary lane).

For each roadway network, the sensitivity of four different congestion levels was tested by incrementally increasing the entering volume (or traffic demand) on the freeway. The four congestion levels tested are shown in table 9.

Table 9. Congestion Levels for FRESIM Sensitivity Analysis.

Congestion Level	Description
Low	1000 veh/h/lane, equivalent to a volume/capacity (V/C) ratio of 0.42.
Medium	1500 veh/h/lane, equivalent to a V/C ratio of 0.63.
High	2000 veh/h/lane, equivalent to a V/C ratio of 0.83.
Very high	2400 veh/h/lane, equivalent to a V/C ratio of 1.0.

The HCM estimates the capacity of a basic freeway segment with a free-flow speed of 113 km/h to be 2400 veh/h/lane assuming ideal conditions.[(2)] In FRESIM, the upper bound of capacity can be limited by using the minimum separation for generation of vehicles parameter. For the sensitivity tests, this value was fixed at 1.5 seconds (default is 1.6 seconds), which equates to a maximum entering volume of 2400 veh/h/lane. The capacity can be limited by the driver behavior logic in some cases; this behavior was seen in the sensitivity study as discussed below.

Testing at V/C ratios above 1.0 was not conducted for the freeway sensitivity tests. With values above 1.0, it was impossible to create a congested state on a basic freeway segment without creating a downstream bottleneck. Because simple basic and merge/diverge networks were used in this study, any demand volume over capacity would still operate at capacity, while creating congested conditions further upstream. Future research into the sensitivity of freeway parameters under overcapacity conditions should be considered, based on the results shown in this study.

The MOEs used to quantify the effects of parameter changes on the quality of traffic flow are shown in table 10.

Table 10. FRESIM MOEs for Sensitivity Analysis.

Measure of Effectiveness	Description
Throughput (veh/h/lane)	Measures the volume of vehicles traveling through a uniform segment. By gradually increasing the entering demand volume, the capacity of the segment was estimated by noting at what point the actual volume no longer matched the entering demand volume. This MOE was used for the basic, merge, diverge, and weave networks. However, it was not used for the system network because there are different segment types within the system, and each segment type has a different capacity.
Vehicle-kilometers of travel (veh-km/h)	Measures the number of vehicles traveling through a segment or multiple segments while taking into account the length of the segments. This MOE, which often is used for freeway system analyses, was only used for the system network as a surrogate to throughput, as it indirectly measures the capacity of the system while also accounting for the length of the network.
Average speed (km/h)	Measures the average space mean speed over the entire freeway network. This MOE was used on all test networks.
Average density (veh/km/lane)	Measures the average density over the entire freeway network. This MOE was used on all test networks.
Average delay (sec/veh)	Measures the difference in actual travel time and desired travel time (based on the free-flow speed). This MOE was used on all test networks.

The MOEs listed in table 10 were summarized only within the portion of the network that captured the extent of the congestion and experienced the most change in MOEs from one congestion level to the next. Table 11 lists the MOE collection area for each network.

Table 11. FRESIM MOE Collection Areas.

Network Name	MOE Collection Area
One-lane basic segment	Entire 1.6-km length of the freeway segment.
Two-lane basic segment	Same as one-lane basic segment.
Three-lane basic segment	Same as one-lane basic segment.
Two-lane merge area	The length of freeway (including the acceleration lane) beginning with the on-ramp gore area and extending downstream 460 m. This distance was used because the HCM states that 460 m is generally the area of influence at merge and diverge areas; this was found to be fairly accurate based on visual inspection of the CORSIM animation for the merge area networks.
Three-lane merge area	Same as two-lane merge area.
Three-lane diverge area	The 1220 m length of freeway starting at the off-ramp gore area and extending upstream 1220 m. The area of influence was increased to 1220 m because vehicles on the freeway began changing lanes to get in the proper lane 760 m upstream of the actual diverge area itself (based on the 760 m default off-ramp reaction point parameter), which created congestion between 760 and approximately 1220 m upstream of the diverge area.
Three-lane diverge area	Same as two-lane diverge area.
Two-lane weave area	The freeway lanes and auxiliary lane within the 300-m weave area.
Three-lane weave area	Same as two-lane weave area.
System	The entire 5.1 km/h freeway segment, including the auxiliary lanes associated with the on- and off-ramps, but not the ramps themselves.

The FRESIM sensitivity study focused on the car following, lane changing, and free-flow speed parameters, because the other driver behavior parameters shown in table 7 apply to intersections on surface streets. Also, the majority of the other parameters listed in tables 3 through 7 have major impacts on the quality of traffic flow, so they already are known to be very sensitive parameters. For example, reducing the number of lanes from three to two due to a lane blockage, changing a signal control to emergency flashing due to a power outage, or reducing the traffic demand by 20 percent due to a major snowstorm all have major impacts on the quality of traffic flow. Such events are easily discernable as having a major effect on traffic flow, but the more subtle changes in car following and lane changing behavior are not quite as obvious, and are therefore the focus of this sensitivity study.

Tables 12 through 14 display the FRESIM parameters included in the sensitivity analysis. Each parameter was tested at the default value, along with four other values representing incrementally more conservative driver behavior, as would be the case with increasingly severe weather conditions. As a result, the sensitivity tests were one-sided in that they only tested values to one side of the default value. However, a few parameters were tested on both sides, because it was not clear which side represented the more conservative driver behavior (e.g., anticipatory lane change distance).

The car following parameters were tested on the basic segment (one-lane, two-lane, and three-lane), and system networks. The basic segment networks were used to isolate the sensitivity of the car following parameters (without the MOEs being influenced by factors associated with merging or diverging), while the system network was used to show the sensitivity within the context of a real-world network consisting of merges, diverges, and weave areas. Table 12 shows car following FRESIM parameters included in the sensitivity analysis.

Table 12. Car Following FRESIM Parameters Included in Sensitivity Analysis.

FRESIM Parameter	Definition
Car following sensitivity factor	This factor is the primary user input in calculating the desired time (in seconds) headway between a leader-follower vehicle pair. A higher value means more space between vehicles. A different value is specified for each driver type (default = 1.25 to 0.35 s based on driver type, mean = 0.80 s).
Car following sensitivity multiplier	A link-specific multiplier of the car-following sensitivity factor (default = 100%). The multiplier is applied to all driver types and therefore changes the overall mean of the sensitivity factor. This value can be used to calibrate car following behavior on a link-by-link basis.
Pitt car following constant	The minimum distance between the rear of the lead vehicle and front of the following vehicle, regardless of vehicle speed (default = 3.05 m).
Lag acceleration/ deceleration time	The time delay (due to perception/reaction time) for motorists when starting to accelerate or decelerate (default = 0.3 s).
Maximum non-emergency deceleration	The maximum deceleration on level grade and dry pavement in non-emergency conditions (i.e., normal lane changing and car following behavior). Reflects driving habits and not capability of the vehicle (default = 2.44 m/s^2).
Jerk value	The maximum change in acceleration between consecutive intervals (default = 2.13 m/s^3). A higher value results in more aggressive driver behavior.

The lane changing parameters were tested on all of the networks described in table 8, with the exception of the basic one-lane segment network, because lane changes are not possible on a one-lane segment. All other networks test various types of lane change environments, including mandatory lane changes at on- and off-ramps, discretionary lane changes on a basic freeway segment, and anticipatory lane changes upstream of merge areas. Refer to the *TSIS Version 5.1 User's Guide*[(12)] and Halati, Lieu, and Walker[(13)] for a detailed description of the FRESIM vehicle movement logic. The lane changing FRESIM parameters included in the sensitivity analysis are displayed in table 13.

Table 13. Lane Changing FRESIM Parameters Included in Sensitivity Analysis.

FRESIM Parameter	Definition
Time to complete lane change	The time to complete a lane change maneuver (default = 2.0 s). Increasing this value results in more extended, smooth lane changes.
Advantage threshold for discretionary lane change	Used to calculate the relative advantage in making a discretionary lane change (default = 0.4). The advantage (measured in speed and volume) in changing lanes must be greater than the condition in the current lane by a factor of 0.4. Increasing this value decreases the number of lane changes.
Discretionary lane change multiplier	A multiplier used in calculating the desire for discretionary lane changes (default = 0.5). Increasing this value increases the desire for discretionary lane changes.
Gap acceptance parameter	Used to determine the acceptable gap for mandatory lane changes (default = 3). A higher value represents less aggressive driver behavior and fewer lane changes.
Percent cooperative drivers	Percentage of drivers desiring to yield the right-of-way to vehicles attempting to merge ahead of them (default = 20%).
Maximum non-emergency deceleration	The maximum deceleration on level grade and dry pavement in non-emergency conditions (i.e., normal lane changing and car following behavior). Reflects driving habits and not capability of the vehicle (default = 2.44 m/s^2).
Maximum emergency deceleration	The maximum deceleration on level grade and dry pavement in emergency conditions (i.e., sudden stop to prevent a collision). Reflects driving habits and not capability of the vehicle (default = 4.57 m/s^2).
Leader's maximum deceleration as perceived by follower	The maximum deceleration of the lead vehicle in an adjacent lane as perceived by a potential lane-changing vehicle, which is used to determine whether a gap in the adjacent lane is acceptable (default = 4.57 m/s^2).
Anticipatory lane change speed	Vehicles upstream of a merge area will change lanes to avoid the area if the speed of the acceleration lane falls below this threshold (default = 2/3 free-flow speed).
Anticipatory lane change distance	Vehicles upstream of a merge area begin to react (in terms of a potential lane change to avoid congestion related to the merge area) this distance in advance of the acceleration lane (default = 458 m).

The two free-flow speed parameters were tested on all of the test networks. Table 14 shows the free-flow speed FRESIM parameters included in the sensitivity analysis.

Table 14. Free-Flow Speed FRESIM Parameters Included in Sensitivity Analysis.

FRESIM Parameter	Definition
Mean free-flow speed	The desired mean speed of vehicles in the absence of any impedance due to other vehicles or traffic control devices (link specific).
Free-flow speed multiplier	A percentage multiplier for each driver type of the mean free-flow speed. A more aggressive driver type receives a higher multiplier to represent a higher free-flow speed. Together, the multipliers provide a distribution of free-flow speed by driver type (default = 88–112% based on driver type).

NETSIM Analysis Methodology

A number of different geometric scenarios, or networks, were developed to test the sensitivity of the parameters under various roadway configurations using the NETSIM model in CORSIM. The networks developed for the NETSIM sensitivity analysis are shown in table 15. Figures 3 and 4 show the two intersection networks as viewed in the Traffic Editor (TRAFED), the input editor interface for Traffic Software Integrated System (TSIS).

Table 15. NETSIM Sensitivity Analysis Networks.

Network Name	Description
One-lane basic segment	One-lane arterial segment (no intersections or driveways) of 1.6 km in length and free-flow speed of 72 km/h.
Two-lane basic segment	Same as the one-lane basic segment, except with two arterial lanes.
Three-lane basic segment	Same as the one-lane basic segment, except with three arterial lanes.
Single suburban intersection	Five-lane arterial with free-flow speed of 72 km/h intersecting a three-lane collector street with free-flow speed of 48 km/h. The intersection is controlled by a fully actuated traffic signal with protected left-turn phasing, 76-m left-turn bays on all approaches, and a maximum cycle length of 120 s (if all phases max out). This intersection is typical of those found on major arterials in a suburban setting. Figure 3 displays the suburban intersection in TRAFED).
Single urban intersection	Three-lane collector intersecting a two-lane collector, both with free-flow speeds of 48 km/h. The intersection is controlled by a pretimed traffic signal with two phases (one for each roadway with permitted left-turn phasing), 46-m left-turn bays on all approaches, and a fixed cycle length of 80 s. This intersection is typical of those found in urban or downtown settings. Figure 3 displays the urban intersection in TRAFED).
System	3.2-m arterial corridor with four traffic signals at 610-m spacing. The arterial has a free-flow speed of 72 km/h with two through lanes in each direction and 76-m left-turn bays at the traffic signals, and the intersecting minor streets are one lane in each direction with 76-m left- and right-turn bays at the intersections. The traffic signals are controlled by a semiactuated, coordinated plan with a 120-s cycle.

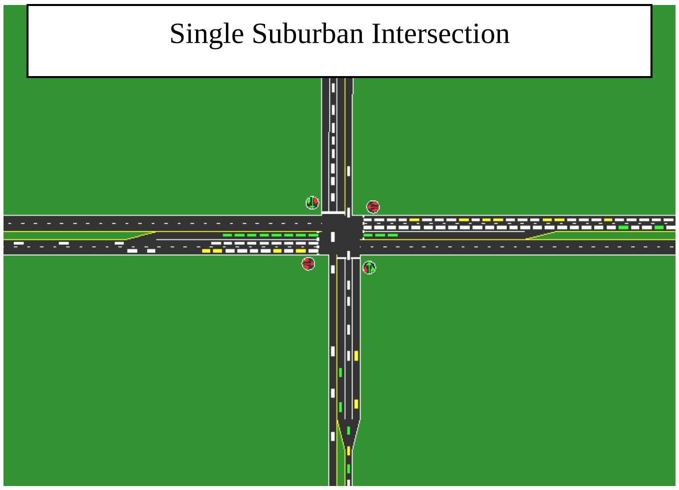


Figure 3. NETSIM Suburban Intersection Network.

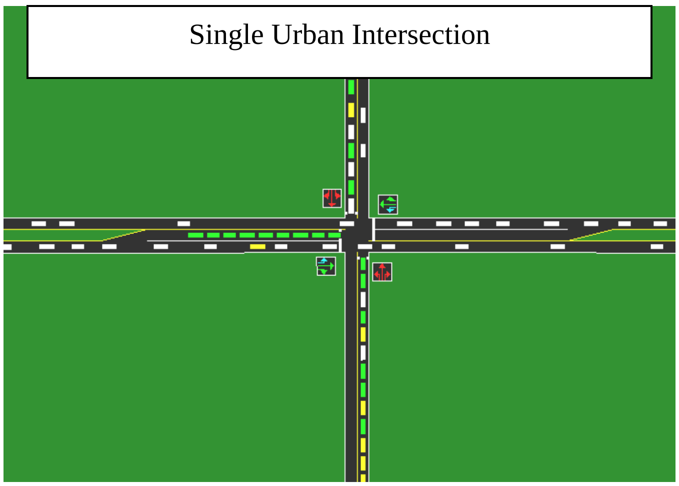


Figure 4. NETSIM Urban Intersection Network.

All networks were assumed to have ideal conditions as defined in the HCM, which includes 3.66-m travel lanes, level grade, no horizontal curves, and no heavy trucks.(2) An analysis period of 1 hour was used for all simulation runs.

For each test network, the sensitivity to four different congestion levels was tested by incrementally increasing the entering volume (or traffic demand) on the entry links. The four congestion levels tested on the basic one-, two-, and three-lane networks are listed in table 16.

Table 16. Congestion Levels for NETSIM Sensitivity Analysis.

Congestion Level	Description
Low	800 veh/h/lane, equivalent to a V/C ratio of 0.4.
Medium	1200 veh/h/lane, equivalent to a V/C ratio of 0.6.
High	1600 veh/h/lane, equivalent to a V/C ratio of 0.8.
Very high	2000 veh/h/lane, equivalent to a V/C ratio of 1.0.

The HCM does not provide guidance on the segment capacity of arterial streets, mainly because the capacity on arterials is determined by traffic signals and not the segment characteristics between traffic signals. However, it is clear that the segment capacity of arterials is generally lower than on freeways due to the lower free-flow speeds and increased friction effects (driveway access, on-street parking, narrow lanes, turning vehicles, etc.). Thus, a capacity of 2000 veh/h/lane was assumed for the basic arterial test networks based on a free-flow speed of 72 km/h. Even though this is just an estimate, the purpose of this study is to test relative sensitivity of different parameters and not to determine the absolute value of capacity or other MOEs.

As mentioned previously in the FRESIM analysis methodology, the minimum separation for generation of vehicles parameter can be used to limit the upper bound of capacity. However, this parameter is not available in NETSIM. As a result, segment volumes as high as 2700 veh/h/lane on a one-lane arterial and 2600 veh/h/lane on a two-lane arterial, assuming a free-flow speed of 72 km/h, were achieved in the current version of NETSIM. These values are higher than the capacity of typical freeways and are not realistic for an arterial segment. Based on this, it is recommended that the minimum separation for generation of vehicles parameter be available in NETSIM with an appropriate default value reflecting a realistic capacity of arterials, such as 1.8 s (equivalent to 2000 veh/h/lane).

For the single suburban intersection, single urban intersection, and system networks, the entering demand volume on all approaches was incrementally increased to achieve V/C ratios of approximately 0.6, 0.8, 1.0, and 1.1. The highest volume scenario was limited to a V/C ratio of 1.1 because ratios higher than 1.1 resulted in queue spillback beyond the limits of the network; therefore, the MOEs would not reflect the extent of the congestion.

Table 17 displays the MOEs used to measure the quality of traffic flow under the various network and volume scenarios for the NETSIM cases.

Table 17. NETSIM MOEs for Sensitivity Analysis.

Measure of Effectiveness	Description
Throughput (veh/h/lane)	Measures the volume of vehicles traveling through a uniform segment or intersection. By gradually increasing the entering demand volume, the capacity of the segment or intersection can be estimated by noting at what point the actual volume no longer matches the entering demand volume. This MOE was used on the all networks except the system network.
Vehicle-kilometers of travel (veh-km/h)	Measures the number of vehicles traveling through a segment or multiple segments while accounting for the length of the segments. This MOE, which is often used for system analyses, was used for the system network only as a surrogate to throughput, as it indirectly measures the capacity of the system when incrementally increasing the entering demand volume, until the vehicle-miles of travel no longer increases at a commensurate rate.
Average speed (km/h)	Measures the average space mean speed over the entire network. This MOE was used on the basic and system networks. However, it was not used on the single intersection networks, because stopped delay was deemed a more appropriate MOE at an intersection level.
Stopped delay (s/veh)	Measures the time spent stopped due to the effects of a traffic signal. This MOE was used on the single suburban and urban intersection networks because it measures the quality of service given by a traffic signal. Control delay was not used here because it is a function of the free-flow speed, and free-flow speed is a parameter in the sensitivity analysis. Thus, control delay would not give a consistent comparison when testing the free-flow speed.
Average delay (s/veh)	Measures the difference in actual travel time and desired travel time. This MOE, used on all test networks, takes into account delays due to traffic control devices and to the interaction with adjacent vehicles.
Number of lane changes (lane changes/h)	Measures the total number of lane changes made on the network. This MOE, used on all test networks, is not a direct measure of the quality of traffic flow, but it was included because it is a helpful measure in understanding why the other MOEs did or did not change significantly and how the parameters affect lane changing behavior.

The MOEs listed in table 17 were only summarized within the portion of the network that captured the extent of the congestion and experienced the most change in MOEs from one congestion level to the next. Table 18 lists the MOE collection area for each network.

The simulation parameters chosen for the arterial sensitivity testing included the car following, lane changing, free-flow speed, discharge headway, startup lost time, and turning speed parameters within NETSIM. As mentioned previously in the FRESIM analysis methodology, the majority of other parameters identified in section 4 as being impacted by weather events already are known to have a major impacts on the quality of traffic flow; therefore they were not included in this sensitivity analysis.

Table 18. NETSIM MOE Collection Areas.

Network Name	MOE Collection Area
One-lane basic segment	The entire 1.6-km length of the segment.
Two-lane basic segment	Same as the one-lane basic segment.
Three-lane basic segment	Same as the one-lane basic segment.
Single suburban intersection	Averaged (weighted based on the approach volume) over all intersection approaches.
Single urban intersection	Averaged (weighted based on the approach volume) over all intersection approaches.
System	Averaged over the major street links only.

Tables 19 through 24 display the NETSIM parameters included in the arterial sensitivity analysis. Each parameter was tested at the default value, along with four other values representing incrementally more conservative driver behavior, as would be the case with increasingly severe weather conditions. As a result, the sensitivity tests were one-sided in that they only test values to one side of the default value. However, a few parameters were tested on both sides because it was not clear which side represented the more conservative driver behavior.

NETSIM only has one car following parameter, compared to six in FRESIM. In NETSIM, the impacts of traffic control devices and lane changing maneuvers to prepare for downstream turning movements often control the vehicle movement logic. Thus, a detailed car following logic in NETSIM is not as critical to modeling realistic traffic flow as it is in FRESIM. On the other hand, the lane changing logic in NETSIM is quite detailed, reflected in the fact that there are 15 NETSIM lane changing parameters. Refer to the *TSIS Version 5.1 User's Guide*(12) and Halati, Lieu, and Walker(13) for a detailed description of the vehicle movement logic in NETSIM. Table 19 shows the car following NETSIM parameter included in the sensitivity analysis.

Table 19. Car Following NETSIM Parameter Included in Sensitivity Analysis.

NETSIM Parameter	Definition
Time to react to sudden deceleration of lead vehicle	The amount of time for a driver to begin decelerating after the leader begins a sudden deceleration due to perception/reaction time (default = 1.0 s).

The lane changing parameters were tested on all the test networks, except the basic one-lane and urban intersection networks (one through lane in each direction) because lane changes are not possible on one-lane roadways. Table 20 shows the lane changing NETSIM parameters included in the sensitivity analysis.

Table 20. Lane Changing NETSIM Parameters Included in Sensitivity Analysis.

NETSIM Parameter	Definition
Driver type factor	This factor is used to calculate a driver's "intolerable" speed—the speed below which a driver begins looking for a lane change (default = 25). A higher value means drivers will have a higher intolerable speed and thus will look for lane changes more often.
Urgency threshold	A driver's desire to change lanes becomes more urgent as he or she gets closer to the object requiring a lane change (lane drop or slow-moving leader). After a driver's urgency factor (based on driver aggressiveness and distance to lane-change object) exceeds this factor, then the acceptable deceleration for changing lanes begins decreasing (default = 0.2).
Minimum deceleration for a lane change	A driver's acceptable deceleration (or risk) for lane changes varies depending on his or her urgency. This value defines the acceptable deceleration when a driver's urgency for changing lanes is very low. Decreasing this value decreases the amount of risk a driver is willing to take and thus decreases the number of lane changes (default = 1.52 m/s^2).
Difference in minimum /maximum deceleration for mandatory lane changes	A driver's acceptable deceleration (or risk) for mandatory lane changes can vary depending on his or her urgency. This factor, measuring the difference in the minimum and maximum acceptable decelerations, defines *how much* the acceptable deceleration can vary. The default value (3.05 m/s^2) means the minimum and maximum acceptable acceleration can vary as much as 3.05 m/s^2.
Difference in minimum/ maximum deceleration for discretionary lane changes	A driver's acceptable deceleration (or risk) for discretionary lane changes can vary depending on his or her urgency. This factor, measuring the difference in the minimum and maximum acceptable decelerations, defines *how much* the acceptable deceleration can vary. The default value (1.52 m/s^2) means the minimum and maximum acceptable acceleration can vary as much as 1.52 m/s^2.
Safety factor	This factor represents the amount of caution by a lane changer (default = 0.8). For example, if the minimum acceptable deceleration is 3.05 m/s^2, then the acceptable deceleration with the safety factor is 10 x 0.8 = 2.44 m/s^2.
Headway at which all vehicles attempt lane change	The headway below which all drivers will attempt a lane change (default = 2.0 s). Increasing this value results in drivers attempting fewer lane changes.
Headway at which no vehicles attempt lane change	The headway above which no drivers will attempt a lane change (default = 5.0 s). Increasing this value results in drivers attempting more lane changes.
Time to react to sudden deceleration of lead vehicle	This factor is used to calculate a driver's "intolerable" speed—the speed below which a driver begins looking for a lane change (default = 25). A higher value means drivers will have a higher intolerable speed and therefore will look for lane changes more often.
Duration of a lane change	The time to complete a lane change maneuver (default = 3.0 s). This is also the minimum time after a lane change is initiated that another lane change can begin. Increasing this value results in more extended, smoother lane changes.
Percent drivers who cooperate with lane changer	The percentage of drivers who will slow down to allow a lane change in front of them (default = 50%). Increasing this value results in more lane change opportunities.
Distance over which drivers perform lane change	The mean distance for a driver to contemplate and complete a lane change (default = 91.4 m). Higher values result in drivers seeking lane changes over a longer distance and therefore make a smoother lane change.

Table 20. Lane Changing NETSIM Parameters Included in Sensitivity Analysis (continued).

NETSIM Parameter	Definition
Distribution of distance to attempt a lane change	A percentage multiplier for each driver type of the mean lane change distance (default ranges from 125–75%).
Deceleration of lead vehicle	The maximum deceleration rate of a lead vehicle (default = 3.66 m/s^2). A higher value results in fewer acceptable gaps (because followers will require larger gaps) and fewer lane changes.
Deceleration of following vehicle	The maximum deceleration rate of a following vehicle (default = 3.66 m/s^2). A higher value means followers will accept smaller gaps and therefore make more lane changes.

The free-flow speed parameters were tested on all the test networks. The two NETSIM free-flow speed parameters are the same as those in FRESIM; however, the default multipliers are slightly different in each model. Table 21 shows the free-flow speed NETSIM parameters included in the sensitivity analysis.

Table 21. Free-Flow Speed NETSIM Parameters Included in Sensitivity Analysis.

NETSIM Parameter	Definition
Mean free-flow speed	The desired mean speed of vehicles in the absence of any impedance due to other vehicles or traffic control devices (link specific).
Free-flow speed multiplier	A percentage multiplier for each driver type of the mean free-flow speed. A more aggressive driver type receives a higher multiplier to represent a higher free-flow speed. Together, the multipliers provide a distribution of free-flow speed by driver type (default = 75–127 percent based on driver type).

The queue discharge headway, startup lost time, and turning speed parameters are only applicable at intersections and thus were tested on all the networks except for the basic segment networks. Tables 22 through 24 show the discharge headway, startup lost time, and turning speed NETSIM parameters included in the sensitivity analysis, respectively.

Table 22. Discharge Headway NETSIM Parameters Included in Sensitivity Analysis.

NETSIM Parameter	Definition
Mean discharge headway	The mean headway between vehicles discharging from a standing queue (mean = 1.8 s).
Discharge headway multiplier	A percentage multiplier for each driver type of the mean discharge headway (default ranges from 170–50%).

Table 23. Startup Lost Time NETSIM Parameters Included in Sensitivity Analysis.

NETSIM Parameter	Definition
Mean startup delay	The mean delay (due to perception/reaction time) of the first vehicle in a queue due to a traffic signal (default = 2.0 s).
Startup lost time multiplier	A percentage multiplier for each driver type of the mean startup delay (ranges from 218–23%).

Table 24. Turning Speed NETSIM Parameters Included in Sensitivity Analysis.

NETSIM Parameter	Definition
Maximum allowable left-turn speed	The speed at which vehicles making a left turn will travel through the turn if unimpeded by other vehicles (default = 6.71 m/s).
Maximum allowable right-turn speed	The speed at which vehicles making a right turn will travel through the turn if unimpeded by other vehicles (default = 3.96 m/s).

Data Processing Procedure

Overall, approximately 45,000 individual CORSIM simulation runs were processed for the sensitivity analysis: 25,000 in FRESIM and 20,000 in NETSIM. The need for the large number of runs becomes clear when considering the following for the FRESIM runs:

- **Parameters—**Eighteen total FRESIM parameters were tested (see tables 3 through 7).
- **Parameter values—**Each parameter was tested using the default value and four additional values representing incrementally more conservative driver behavior, as would be expected under adverse weather.
- **Networks—**Each parameter was tested on an average of seven FRESIM networks (car following parameters tested on 4 networks, lane changing on 9 networks, and free-flow speed on 10 networks) (see table 8).
- **Congestion level—**Each FRESIM network was tested at four different congestion levels (see table 9).
- **Simulation runs—**Ten simulation runs were performed for each scenario to take into account the stochastic variations of the simulation model.

Therefore, the number of total FRESIM runs equals approximately 25,000 (18x5x7x4x10).

Due to the large number of simulation runs, the process of creating the CORSIM input files and summarizing the output files was largely automated. The data processing was completed through four steps, described below.

Step 1—Create the CORSIM input files.

A customized script (in both Microsoft® Visual Basic® and C++®) was created that automatically generated new TRF files by taking a base input file and changing one or more parameters at a time. As a result, thousands of input files could be created with a single "Do Loop" command, changing the value of one or more parameters multiple times. A spreadsheet was created with all the desired network-congestion level-parameter value combinations, which was read by the script to create the input files.

Step 2—Run CORSIM 10 times for each input file, and create an output file summarizing the relevant MOEs from the 10 runs.

The multirun function available in TSIS 5.1 (the simulation environment that includes CORSIM) was used to run CORSIM 10 times for each input file. The "Output Processor" function available in TSIS was also used to create an output file in Microsoft® Excel® format summarizing the mean and standard deviations of the MOEs for the 10 runs. The random number seeds were changed for each of the 10 runs.

Step 3—Copy all relevant MOE data from the output files into a single database.

Customized Microsoft® Visual Basic® macros were created that copied the relevant MOE data from the thousands of output files into two databases, one each for the FRESIM and NETSIM runs. The macros also calculated t-values to test the statistical significance of the results (at a 95 percent confidence interval).

Step 4—Create a one-page summary of MOEs for each parameter-network combination.

One-page summaries for each parameter-network combination (e.g., sensitivity of the car following factor on basic two-lane freeway) were created using customized Microsoft® Visual Basic® macros that read the values from the database created in step 3.

The end product of the data processing is a one-page summary for each parameter-network combination (e.g., sensitivity of mean free-flow speed on basic one-lane freeway network). These one-page summaries provided a useful tool for evaluating the sensitivity of each parameter. Tables 25 through 29 and figures 5 through 9 display a sample of the information available on a single one-page summary (formatting requirements of the report precluded the original format of the one-page summary from being displayed). The results from these figures and tables represent the results of testing the car following sensitivity multiplier on the FRESIM system network, which, as will be discussed later, is one of the most sensitive parameters tested.

Table 25. General Information for Sample Sensitivity Test.

Component	Description
Parameter name	Car following sensitivity multiplier
Parameter type	Car following
Test network	System
Model	FRESIM
Input level	Link
TRAFED location	Double-click a link -> “General” tab
Record type/field(s):	Record type 20/Field 17
Default value	100
Sensitivity range	100, 125, 150, 175, 200
Definition	This value adjusts the car following sensitivity factor by a multiplier for all vehicles on a given link. The car following sensitivity factor is the primary variable in determining the desired headway of a vehicle following another vehicle.

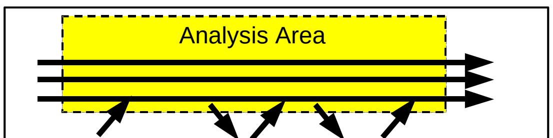


Figure 5. Analysis Area Information for Sample Sensitivity Test.

Table 26. Vehicle-Kilometers Traveled Table for Sample Sensitivity Test.

Entering Volume (veh/h/ln)	**VEHICLE-KILOMETERS OF TRAVEL (veh-km/hr)**				
	Car Following Sensitivity Multiplier				
	100 *	125	150	175	200
1000	17728	17733 (0%)	17731 (0%)	17724 (0%)	17724 (0%)
1500	24787	24770 (0%)	24733 (0%)	24740 (0%)	**23930 (-3%)**
2000	31102	**29363 (-6%)**	**27945 (-10%)**	**26066 (-16%)**	**23939 (-23%)**
2500	31058	**29309 (-6%)**	**27898 (-10%)**	**26036 (-16%)**	**24004 (-23%)**

Notes: * = Default value.
(XX%) = Percent difference from default value.
Bold value = Value is statistically different from default value (95th percentile confidence level).

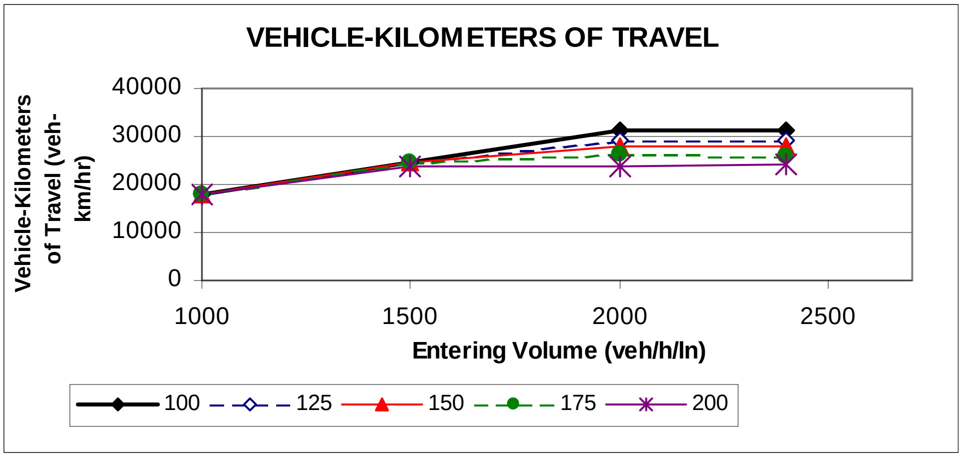


Figure 6. Vehicle-Kilometers Traveled Graph for Sample Sensitivity Test.

Table 27. Average Speed Table for Sample Sensitivity Test.

Entering Volume (veh/h/ln)	AVERAGE SPEED (km/h)				
	Car Following Sensitivity Multiplier				
	100 *	125	150	175	200
1000	107.0	**107.0 (-1%)**	**106.0 (-1%)**	**105.0 (-2%)**	**104.0 (-3%)**
1500	105.0	**103.0 (-2%)**	**100.0 (-5%)**	**92.1 (-12%)**	**61.4 (-42%)**
2000	81.0	**66.3 (-18%)**	**62.2 (-23%)**	**58.1 (-28%)**	**53.2 (-34%)**
2500	72.7	**66.6 (-8%)**	**62.7 (-14%)**	**57.6 (-21%)**	**54.0 (-26%)**

Notes: * = Default value.
(XX%) = Percent difference from default value.
Bold value = Value is statistically different from default value (95th percentile confidence level).

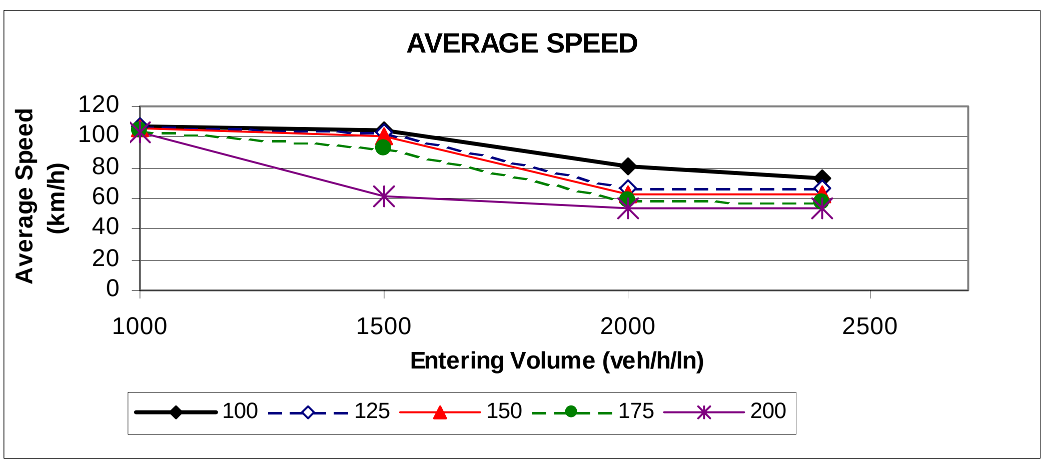


Figure 7. Average Speed Graph for Sample Sensitivity Test.

Table 28. Average Delay Table for Sample Sensitivity Test.

Entering Volume (veh/h/ln)	AVERAGE DELAY (s/veh)				
	Car Following Sensitivity Multiplier				
	100 *	125	150	175	200
1000	8.1	**9.1 (12%)**	**10.3 (27%)**	**12.1 (49%)**	**14.2 (74%)**
1500	12.0	**14.8 (24%)**	**20.3 (70%)**	**36.4 (204%)**	**137. (1040%)**
2000	63.8	**114. (78%)**	**133. (108%)**	**153. (140%)**	**182. (186%)**
2500	89.5	**113. (26%)**	**130. (46%)**	**157. (75%)**	**178. (98%)**

Notes: * = Default value.
(XX%) = Percent difference from default value.
Bold value = Value is statistically different from default value (95th percentile confidence level).

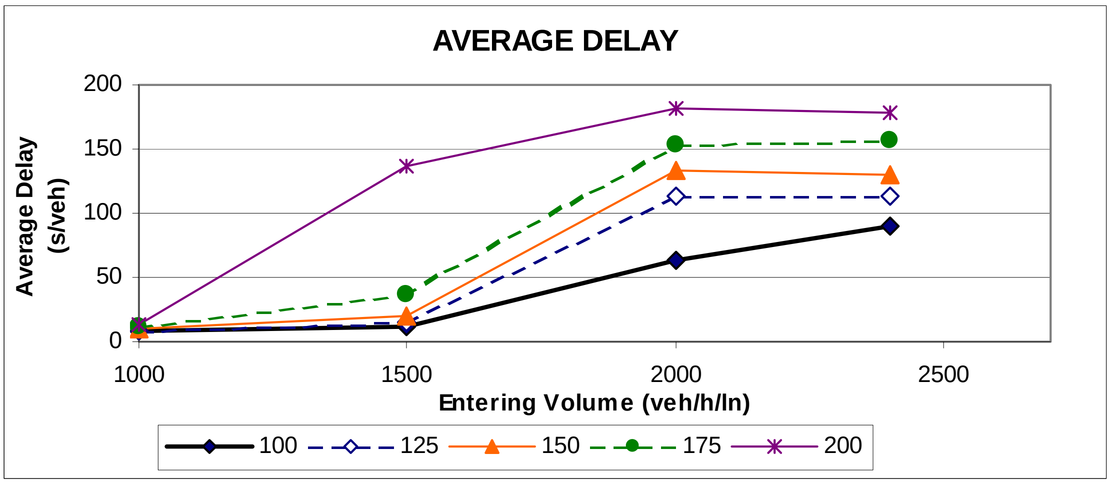


Figure 8. Average Delay Graph for Sample Sensitivity Test.

Table 29. Average Density Table for Sample Sensitivity Test.

Entering Volume (veh/h/ln)	AVERAGE DENSITY (veh/km/ln)				
	Car Following Sensitivity Multiplier				
	100 *	125	150	175	200
1000	**10.9**	**10.9 (1%)**	**11.0 (1%)**	**11.1 (2%)**	**11.3 (4%)**
1500	**15.5**	**15.8 (2%)**	**16.3 (5%)**	**17.9 (15%)**	**26.5 (71%)**
2000	**26.2**	**32.6 (24%)**	**32.4 (24%)**	**31.4 (20%)**	**31.4 (20%)**
2500	33.0	33.2 (1%)	32.1 (-3%)	**31.7 (-4%)**	**31.0 (-6%)**

Notes: * = Default value.
(XX%) = Percent difference from default value.
Bold value = Value is statistically different from default value (95th percentile confidence level).

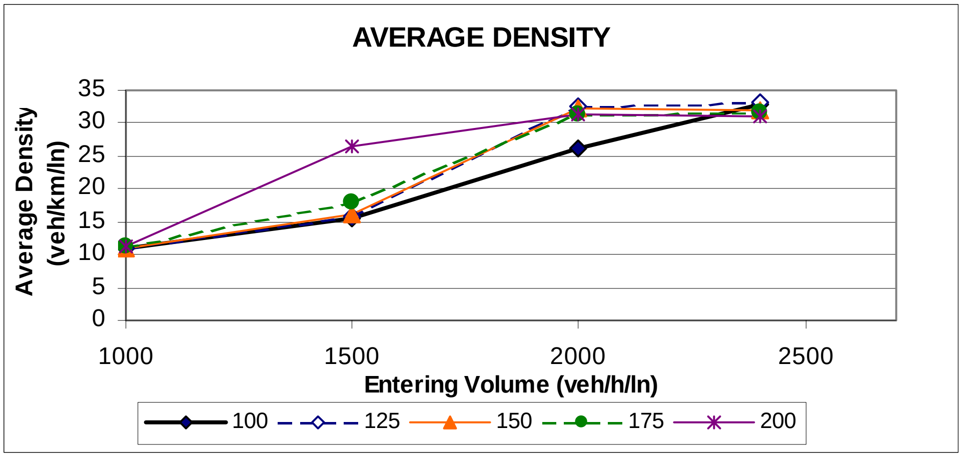


Figure 9. Average Density Graph for Sample Sensitivity Test.

The summary graphs shown above use the entering volumes as the X-axis, which could be different than the actual volumes in the at-capacity scenarios. Thus, the graphs do not match traditional speed-volume-density graphs typically found in the HCM or other traffic flow theory applications. Demand volume was used in this study because the objective was to understand the sensitivity of the parameters under different uniform scenarios, so it was important to keep the X-axis constant to see how the MOEs varied under each parameter value. Using the actual volume in the X-axis would make it more difficult to directly compare the results of each parameter value, especially when the parameter values experience a slightly different actual volume for the at-capacity scenarios.

FRESIM Sensitivity Analysis Results

The sensitivity test results for each parameter-network scenario were examined and a number of general trends from the sensitivity study were observed, including:

- Most of the parameters showed no sensitivity at the lower congestion levels (entering volumes of 1000 and 1500 veh/hr/lane). In only a few instances did the most extreme sensitivity value produce a statistically significant difference (at a 95 percent confidence interval) from the default value.
- An entering volume of 2000 veh/hr/lane (approximate V/C ratio of 0.83) experienced more sensitivity within the parameters than that shown with 2400 veh/hr/lane (approximate V/C ratio of 1.0). This trend was likely caused because the at-capacity condition allowed less variability in driver behavior due to more closely spaced vehicles and less maneuverability.
- Average delay was the most sensitive MOE. Average speed and average density were equally sensitive, and less sensitive than average delay, while throughput and vehicle-miles of travel were the least sensitive.
- Overall, the parameters became more sensitive as the network type became more complex. Thus, the system network generally experienced more sensitivity than the

basic three-lane network, which in turn experienced more sensitivity than the basic one-lane network.

As stated earlier, the majority of the sensitivity tests were designed as one-sided tests, meaning the parameter values were varied on one side of the default value to represent more cautious driver behavior, as would be expected during adverse weather. Based on this one-sided methodology, it was expected that the parameters would experience a general degradation in MOEs (i.e., average speed decreasing and average delay increasing) when changing the parameter values to represent more conservative driver behavior. However, this was not always the case. In fact, the parameters were divided into three "sensitivity groups" based on their general effect on the MOEs, as shown in table 30.

Table 30. CORSIM Parameter Sensitivity Groups.

Sensitivity Group	Description
Expected	Parameter values that consistently produced degradation in MOEs.
Inconsistent	Parameter values that showed no consistent trend between more conservative driver behavior and MOEs.
No effect	Parameter values that had virtually no effect on the MOEs in any of the network-congestion level scenarios.

Figures 10 through 12 show the sensitivity of average speed on the freeway system network for three parameters representing each sensitivity group. As shown in these figures, the Pitt car following constant follows a consistent and expected trend, the maximum emergency deceleration does not follow a consistent trend, and the jerk value shows no sensitivity at all.

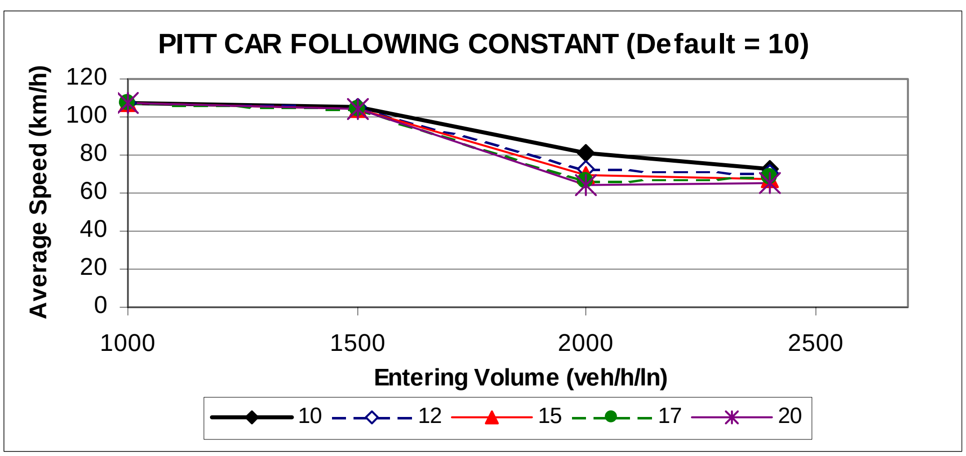


Figure 10. Sensitivity of Pitt Car Following Constant on Freeway System Network—Example of "Expected" Sensitivity Group.

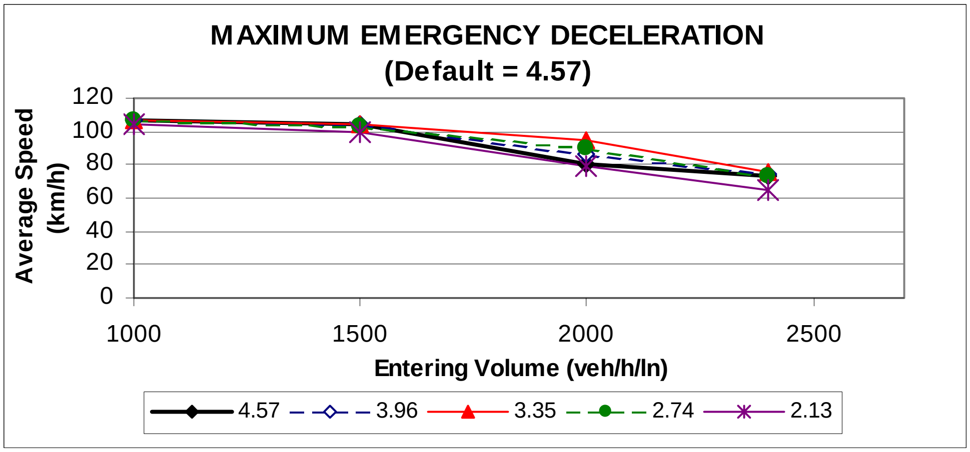


Figure 11. Sensitivity of Maximum Emergency Deceleration on Freeway System Network—Example of "Inconsistent" Sensitivity Group.

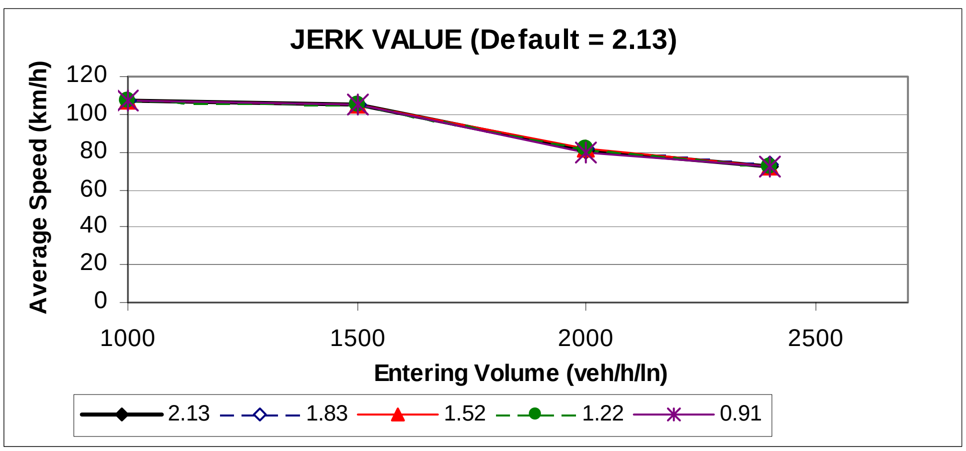


Figure 12. Sensitivity of Jerk Value on Freeway System Network—Example of "No Effect" Sensitivity Group.

Tables 31 through 33 summarize the general sensitivity of each freeway parameter tested, based on the sensitivity group and general level of sensitivity. Low, medium, or high sensitivity levels are based on an evaluation of the overall sensitivity of the parameter values in each network-congestion level scenario. These are based on relative differences between the parameters and not an absolute sensitivity level.

Sensitivity of Car Following Parameters

Table 31 summarizes the sensitivity of each FRESIM car following parameter.

Table 31. General Sensitivity of FRESIM Car Following Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Car following sensitivity factor	0.3,* 0.2, 0.1, 0.0**	No Effect	Low	This parameter overall has little sensitivity when changing the standard deviation of the sensitivity factor by driver types (but keeping the mean constant).
Car following sensitivity multiplier	100,* 125, 150, 175, 200	Expected	High	The most sensitive car following parameter. Value of 125 yields statistically different MOEs than default at medium congestion levels (V/C of 0.63 and higher).
Pitt car following constant	10,* 12, 15, 17, 20	Expected	Medium	CORSIM only allows values from 3 to 10. A modification was made to allow larger values. A value of 12 yields statistically different MOEs than default at higher congestion levels (V/C of 0.83 and higher).
Lag acceleration /deceleration time	1, 3,* 5, 7, 9	Expected	Medium	MOEs worsen as value increases. Value of 5 yields statistically different MOEs on system network than default value. Value of 1 much more sensitive than other values.
Jerk value	2.14,*1.83, 1.52, 1.22, 0.91	No Effect	Low	Values show no statistically significant sensitivity under any network-congestion level scenario.

Notes: * - Default value.
** - These values represent the standard deviation of the car following sensitivity factors for each of the 10 driver types. The default values (range from 1.25-0.35 for driver type 1 to 10) equal a mean value of 0.80 and standard deviation of 0.30. Each consecutive alternative has the same mean (0.80) but smaller standard deviation to represent more uniform driver behavior.

The car following sensitivity multiplier parameter is clearly the most sensitive car following parameter and would be the most practical to manipulate when trying to alter car following behavior. Increasing the car following sensitivity multiplier value to 125 percent nearly always (more so at 1500 veh/hr/lane entering volume or higher) resulted in a statistically significant degradation in MOEs from the default. An interesting trend was observed with the car following sensitivity multiplier on the basic two-lane segment and three-lane segment networks: increasing the multiplier resulted in increasingly degraded MOEs for the lower entering volume scenarios, but increasingly improved MOEs for the at-capacity scenarios. One possible inference from this finding is that more conservative car following behavior results in lower quality of service in uncongested conditions, but improved quality of service in congested conditions. However, this finding was not duplicated with the other car following parameters.

The Pitt car following constant and lag acceleration/deceleration time parameters, while not as sensitive as the car following sensitivity multiplier, showed consistent and expected results. They also should be considered when attempting to calibrate car following behavior. A Pitt car following constant value of 3.66 m yielded statistically degraded MOEs when compared to the default, but generally only at the higher congestion scenarios (entering volume of 2000 veh/h/lane or higher). (Note: The current version of CORSIM only allows values of the Pitt constant to vary from 3 to 10. A modification was made to allow larger values for this study.) The lag acceleration/deceleration time values of 5.0 s or higher showed statistical differences at an entering volume of 2000 veh/h/lane on the system network, but the values were statistically different only at the highest congestion level (2400 veh/h/lane) on the basic segment networks.

The jerk value and car following sensitivity factor showed no sensitivity under any of the scenarios. However, this does not imply that these parameters have no sensitivity whatsoever. In fact, further testing with different networks and/or at a more detailed analysis level would provide a more complete depiction of the parameter's sensitivity and might reveal a sensitivity that was not evident in these scenarios.

Sensitivity of Lane Changing Parameters

Table 32 summarizes the sensitivity of each FRESIM lane changing parameter. The lane changing parameters were generally not as stable as the car following parameters, as many produced no clear trends in the MOEs. Some parameters produced a clear trend in one network, but then the opposite trend in another network (e.g., anticipatory lane change speed). On the other hand, other parameters consistently showed no clear trend in every network (e.g., maximum emergency deceleration). It was interesting that the maximum emergency deceleration and the leader's maximum deceleration as perceived by follower parameters had identical impacts on the MOEs in every network and volume level, prompting the question of why there are two different parameters in the model that yield identical results.

The time to complete lane change parameter produced consistent and expected results at a medium level of sensitivity. Based on this finding, this parameter should be considered first when attempting to calibrate lane changing behavior. The advantage threshold for discretionary lane change, discretionary lane change multiplier, gap acceptance parameter, and percent cooperative drivers parameters showed no sensitivity under any of the scenarios. However, as stated previously, it should not be inferred that these parameters have no sensitivity whatsoever, but rather a more detailed analysis should be completed under different networks and/or a more detailed analysis level to get a more complete depiction of the true parameter sensitivity.

Table 32. General Sensitivity of FRESIM Lane Changing Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Time to complete lane change	2.0,* 2.5, 3.0, 3.5, 4.0	Expected	Medium	Value of 3.0 yields statistically different MOEs for most networks at higher congestion levels.
Advantage threshold for discretionary lane change	0.4,* 0.5, 0.6, 0.7, 0.8	No Effect	Low	This parameter overall has little sensitivity, with the exception of average delay at the highest congestion level.
Discretionary lane change multiplier	5,* 4, 3, 2, 1	No Effect	Low	This parameter overall has little sensitivity.
Gap acceptance parameter	3,* 4, 5, 6	No Effect	Low	This parameter overall has little sensitivity.
Percent cooperative drivers	20,* 30, 40, 50, 100	No Effect	Low	This parameter has very little sensitivity, even at the maximum value (100).
Maximum non-emergency deceleration	2.44,* 2.13, 1.83, 1.52, 1.22	Inconsistent	Medium	MOEs improve as value decreases. Value of 1.83 yields statistically different MOEs on most scenarios.
Maximum emergency deceleration	4.57,* 3.96, 3.35, 2.74, 2.13	Inconsistent	Medium	MOEs improve as value decreases, except for a value of 2.13, which often yields worse MOEs.
Leader's maximum deceleration as perceived by follower	4.57,* 3.96, 3.35, 2.74, 2.13	Inconsistent	Medium	Identical results as maximum emergency deceleration parameter.
Anticipatory lane change distance	762, 610, 457,* 305, 152	Inconsistent	Medium	No clear trend between distance and MOEs (different trend in each network).
Anticipatory lane change speed	69,* 56, 48, 40, 32	Inconsistent	Medium	No clear trend between this parameter and MOEs. System and merge networks show improvement in MOEs as speed decreases, but weave network shows degradation in MOEs.

Notes: * - Default value.

Sensitivity of Free-Flow Speed Parameters

Table 33 summarizes the sensitivity of each FRESIM free-flow speed parameter.

Table 33. General Sensitivity of FRESIM Free-Flow Speed Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Mean free-flow speed	113,* 97, 81, 64, 48	Expected	High	The most sensitive of all parameters tested. A value of 60 yielded statistically different MOEs than the default value for all networks.
Free-flow speed multiplier **	0.78,* 0.54, 0.27, 0.00**	Inconsistent	Medium	No clear trend between standard deviation and MOEs (different trend in each network). Basic networks have high sensitivity at higher congestion levels but other networks show little sensitivity.

Notes: * - Default value.

** - These values represent the standard deviation of the free-flow speed multiplier for each of the 10 driver types. The default values (range from 0.88 to 1.22 for driver type 1 to 10) equal a mean value of 1.0 and standard deviation of 0.78. Each consecutive alternative has the same mean (1.0) but smaller standard deviation to represent more uniform driver behavior.

The mean free-flow speed parameter was the most sensitive of all parameters studied. A free-flow speed of 97 km/h yielded statistically different results under all scenarios compared to the default value (113 km/h). This sensitivity study confirms past research showing that the free-flow speed parameter is a crucial parameter to alter when modeling weather events on freeway networks. However, the free-flow speed multiplier parameter, which was tested by changing the distribution of speed by driver type while maintaining the same mean speed, showed no clear trend in its impact on the MOEs. Further, changing the multipliers so that each driver type has the same free-flow speed (or zero standard deviation) yielded average speeds equal to the free-flow speed on the basic segment networks, which is an unrealistic result at the higher volume levels because all other test scenarios showed a gradual decrease in average speed with an increase in entering volume.

NETSIM Sensitivity Analysis Results

The sensitivity results for each NETSIM parameter-network scenario, like the example results shown in tables 25 through 29 and figures 5 through 9, were examined and a number of trends from the sensitivity study were observed, including:

- The number of lane changes was the most sensitive MOE relative to the other MOEs. Average delay and average speed both showed moderate sensitivity, while throughput and vehicle-miles of travel displayed the least sensitivity relative to the other MOEs.
- For the basic segment networks, the parameters became increasingly sensitive as the V/C ratio increased. However, like the freeway parameters, the arterial parameters were generally slightly more sensitive at the just-below capacity (V/C ratio around 0.8) than the at-capacity conditions. This trend is thought to occur because the at-

capacity condition allowed less variability in driver behavior due to more closely spaced vehicles and less maneuverability.

- For the intersection networks, the MOEs degraded dramatically when the V/C ratio approached 1.0.

Tables 34 through 39 summarize the general sensitivity of each network parameter tested based on the sensitivity group (refer to table 30) and general level of sensitivity.

Sensitivity of Car Following Parameters

Table 34 displays the general sensitivity of the NETSIM car following parameter.

Table 34. General Sensitivity of NETSIM Car Following Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Time to react to sudden deceleration of lead vehicle	0.5, 1.0,* 1.5, 2.0, 2.5	Expected	High	Values of 1.5 and higher yield statistically degraded MOEs with basic and system networks under all congestion levels. Intersection networks show slightly less sensitivity.

Notes: * - Default value.

As described previously, there is not a detailed car following model in NETSIM, primarily because the movement of vehicles on surface streets are controlled more by lane changing behavior and reacting to traffic control devices than by basic car following behavior. For the time to react to sudden deceleration of lead vehicle parameter, significant degradation in the MOEs were observed as the parameter value increased for the basic segment and system networks. However, for the single intersection networks, especially the urban intersection, the parameter changes had little effect on the MOEs. The small effect on the intersection networks is logical, given that vehicle movement likely was controlled mainly by reaction to the traffic signal and queues upstream of the signal.

It should be noted that the time to react to sudden deceleration of lead vehicle parameter also affects lane changing behavior, as seen in the next section.

Sensitivity of Lane Changing Parameters

Table 35 displays the general sensitivity of the NETSIM lane changing parameters.

Table 35. General Sensitivity of NETSIM Lane Changing Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Driver type factor	15, 25,* 35, 45, 50	No Effect	Low	No sensitivity, not even at a value of 50, to any network-congestion level combination.
Urgency threshold	2,* 2.5, 3, 4, 5	No Effect	Low	Very low sensitivity. In a few cases, a value of 5 yielded differences of 2-3% from default value, but never at statistically significant level.
Minimum deceleration for a lane change	1.52,* 1.22, 0.91, 0.61, 0.30	Expected	Medium	Statistically significant decreases in number of lane changes (up to 20%), but none for other MOEs.
Difference in minimum/maximum deceleration for mandatory lane changes	3.05,* 2.74, 2.13, 1.83, 1.52	No Effect	Low	Very low sensitivity. MOEs did not change at statistically significant level in any network-congestion level combination.
Difference in minimum /maximum deceleration for discretionary lane changes	1.52,* 1.22, 0.91, 0.61, 0.30	No Effect	Low	Statistical increase in the number of lane changes in some cases under non-congestion level (up to 10%). Very low sensitivity on other MOEs.
Safety factor	0.80,* 0.75, 0.70, 0.65, 0.60	No Effect	Low	Moderate reduction in number of lane changes when safety factor is 0.6 and volumes are high (4–6% reduction). A few cases yielded differences of 1–3%, but no statistical significance.
Headway at which all vehicles attempt lane change	2.0,* 1.8, 1.5, 1.2, 1.0	No Effect	Low	Very low sensitivity. The number of lane changes decreased in all networks (0–4%). Very low sensitivity on other MOEs.
Headway at which no vehicles attempt lane change	5.0,* 4.5, 4.0, 3.5, 3.0	No Effect	Low	Very low sensitivity. The number of lane changes decreased in all networks (maximum 2%). Very low sensitivity on other MOEs.
Time to react to sudden deceleration of lead vehicle	0.5, 1.0,* 1.5, 2.0, 2.5	Expected	High	Values of 1.5 and higher yield statistically degraded MOEs with basic and system networks under all congestion levels. Intersection networks show slightly less sensitivity.
Duration of a lane change	3,* 5, 6, 7, 8	No Effect	Low	Low sensitivity. The number of lane changes decreased slightly (5% maximum at the significant level). Very low sensitivity on other MOEs.
Percent drivers who cooperate with lane changer	10, 25, 50,* 75, 100	No Effect	Low	At value of 10, the number of lane changes drops by up to 12%. A maximum 10% increase in average speed on the suburban intersection with a value of 100 (not a statistically significant difference).
Distance over which drivers perform lane change	91.4,* 152, 214, 274, 335	No Effect	Low	Very low sensitivity.

Table 35. General Sensitivity of NETSIM Lane Changing Parameters (continued).

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Distribution of distance to attempt a lane change	17.1,* 11.4, 6.1, 0.0**	No Effect	Low	No sensitivity was shown, not even a 1% difference at a standard deviation of 0.0.
Deceleration of lead vehicle	3.66,* 3.35, 3.05	Expected	Medium	The number of lane changes decreased dramatically, as much as 100%. The basic networks experienced statistical decreases in average speed (2–4%) and delay (up to 20%).
Deceleration of following vehicle	3.66,* 3.35, 3.05	Expected	Medium	The number of lane changes decreased dramatically, as much as 90%. The basic networks experienced statistical decreases in average speed (1–6%) and delay (up to 44%).

Notes: * - Default value.

** - These values represent the standard deviation of the distance to attempt a lane change for each of the 10 driver types. The default values (range from 125 to 75 percent for driver type 1 to 10) equal a mean value of 100 and standard deviation of 17.1. Each consecutive alternative has the same mean (100) but smaller standard deviation to represent more uniform driver behavior.

As shown in the table, there are 15 lane changing parameters in NETSIM. Of these parameters, 11 had very little sensitivity overall on the MOEs. Typically these parameters had some small, quantifiable change on the number of lane changes, but had very little impact (and not statistically significant) on the other MOEs. This study does not prove that these parameters have no sensitivity whatsoever. Testing of different networks or use of different MOEs could reveal additional sensitivity not discovered in this study. For example, examination of more disaggregate MOEs, such as vehicle trajectory data, could reveal sensitivity of the parameters at a level that is not possible with aggregate MOEs such as average speed over an entire link.

The time to react to sudden deceleration of lead vehicle parameter impacted the number of lane changes dramatically (up to 90 percent increase on the basic segment networks and 30 percent on the other networks). The other MOEs changed at a more modest, but still significant, level.

The minimum deceleration for a lane change had a moderate impact on the number of lane changes (up to 20 percent change), but no statistically significant changes in the other MOEs.

The deceleration of lead vehicle and deceleration of following vehicle parameters showed a medium level of sensitivity (relative to the other parameters), with a significant decrease in the number of lane changes and more moderate, but still statistically significant, change in average speed and average delay. It is interesting that CORSIM will not allow users to enter a value for these parameters less than 3.05 (allowable range of 3.05 to 4.57). Future consideration should be given to widening this allowable range, given that it is one of the few lane changing parameters that has a quantifiable impact on MOEs.

Sensitivity of Free-Flow Speed Parameters

Table 36 displays the general sensitivity of the NETSIM free-flow speed parameters.

Table 36. General Sensitivity of NETSIM Free-Flow Speed Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Mean free-flow speed	72,* 64, 56, 48, 40	Expected	High	Average speed and delay changed significantly at all congestion levels (average speed reduced 12% at 64 km/h and 46% at 40 km/h), but throughput was not as sensitive (no statistical differences).
Free-flow speed multiplier	16,* 11.4, 5.4, 0.0**	Inconsistent	Medium	Reducing the standard deviation improves the MOEs on the basic segment networks (up to 25% increase in average speed), but no statistical differences on other networks.

Notes: * - Default value.
** - These values represent the standard deviation of the free-flow speed multiplier for each of the 10 driver types. The default values (range from 75 to 127 percent for driver type 1 to 10) equal a mean value of 100 and standard deviation of 16.0. Each consecutive alternative has the same mean (100) but smaller standard deviation to represent more uniform driver behavior.

The mean free-flow speed parameter was the most sensitive of all NETSIM parameters studied. For example, lowering the mean free-flow speed from 72 to 40 km/h resulted in a 450 percent increase in total delay and 45 percent decrease in average speed on the basic two-lane segment. This finding that the MOEs are very sensitive to changes in free-flow speed is similar to that found in the FRESIM sensitivity analysis.

The free-flow speed multiplier represents a distribution of free-flow speeds based on driver type. It was found that more uniform free-flow speeds (lower standard deviation) resulted in fewer lane changes. In addition, the other MOEs (except for throughput) improved on the basic segment networks (up to 25 percent increase in average speed), but no statistically significant changes were found on the other networks. The free-flow speed multiplier did not affect the throughput on the basic one-, two-, and three-lane segment networks. The improvement on the basic segment networks were similar to that found in the FRESIM sensitivity analysis.

Sensitivity of Discharge Headway Parameters

Table 37 displays the general sensitivity of the NETSIM discharge headway parameters.

The mean discharge headway is a very sensitive NETSIM parameter, as shown in the table. Generally, as the discharge headway increased, the MOEs became more degraded. Stopped delay was the most affected MOE (up to 1800 percent increases), while the number of lane changes was the least affected MOE (maximum change of 20 percent).

Changing the distribution of the discharge headway multiplier (while maintaining the same mean value) did not statistically impact any of the networks during any congestion level.

Table 37. General Sensitivity of NETSIM Discharge Headway Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Mean discharge headway	1.9,* 2.2, 2.5, 2.7, 3.0	Expected	High	Stop delay increased 1300%, and throughput decreased 35% at 3.0 on the suburban intersection.
Discharge headway multiplier	33.7,* 20.2, 10.1, 0.0**	No Effect	Low	No statistical differences were observed in any network-congestion level combination.

Notes: * - Default value.
** - These values represent the standard deviation of the discharge headway multiplier for each of the 10 driver types. The default values (range from 170 to 50 percent for driver type 1 to 10) equal a mean value of 100 and standard deviation of 33.7. Each consecutive alternative has the same mean (100) but smaller standard deviation to represent more uniform driver behavior.

Sensitivity of Startup Delay Parameters

Table 38 displays the general sensitivity of the NETSIM startup delay parameters.

Table 38. General Sensitivity of NETSIM Startup Delay Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Mean startup delay	1.3,* 1.5, 1.7, 1.9, 2.1	Expected	High	Stop delay increased 47%, and throughput decreased only slightly (2%) at a value of 2.1 on the suburban intersection.
Startup delay multiplier	55,* 37, 16.8, 0.0**	No Effect	Low	No statistical differences were observed in any network-congestion level combination.

Notes: * - Default value.
** - These values represent the standard deviation of the startup delay multiplier for each of the 10 driver types. The default values (range from 218 to 23 percent for driver type 1 to 10) equal a mean value of 100 and standard deviation of 55. Each consecutive alternative has the same mean (100) but smaller standard deviation to represent more uniform driver behavior.

The startup delay parameters had a similar effect on the MOEs as the discharge headway parameters, but with slightly less severity because this parameter only affects the first few vehicles in a queue. For example, throughput and the number of lane changes were impacted minimally (maximum of 2 and 6 percent, respectively). Generally, as the startup delay increased, the MOEs subsequently degraded. Stop delay was the most affected MOE (increases of up to 47 percent), while average speed dropped only up to 10 percent. The changes in average delays were impacted as well (up to 37 percent). The changes in average delays were greatest in the urban network, while the system network was the least impacted network overall.

Changing the distribution of the startup delay multiplier (while maintaining the same mean value) did not statistically impact any of the networks during any congestion level.

Sensitivity of Turning Speed Parameters

Table 39 displays the general sensitivity of the NETSIM turning speed parameters.

Table 39. General Sensitivity of NETSIM Turning Speed Parameters.

Parameter	Parameter Values	Sensitivity Group	Sensitivity Level	Comments
Maximum allowable left-turn speed	35,* 29, 23, 16, 10	Expected	Medium	The largest difference was a 12% increase (which was statistically significant) in stopped delay at 9.7 km/h on the urban intersection.
Maximum allowable right-turn speed	21,* 18, 15, 11, 8	Expected	Medium	The largest difference was a 15% increase (which was statistically significant) in stopped delay at 8 km/h on the urban intersection.

Notes: * - Default value.

Decreasing the turning speeds produced an expected degradation in the MOEs. The MOEs were most affected at the higher congestion levels, as vehicles were more closely spaced and thus delayed more by vehicles turning at a slower rate. Stopped delay was the most affected MOE, as stopped delays increased approximately 10 to 15 percent on the urban intersection during the highest congestion levels. The left- and right-turning speeds were approximately equally sensitive on the test networks.

Summary of Sensitivity Analysis

The purpose of the sensitivity study was to identify the most sensitive weather-related parameters in CORSIM. The study focused on car following, lane changing, and free-flow speed parameters on freeways (FRESIM) and car following, lane changing, free-flow speed, discharge headway, startup lost time, and turning speed parameters on arterial streets (NETSIM). Each test parameter was modeled on various geometric networks and congestion (volume) levels using the default value and then changing the value to represent incrementally more conservative driver behavior, as would occur under adverse weather. The MOEs produced by the default value were then compared to the MOEs produced with the changed parameter values to determine the level of sensitivity the parameter has on the MOEs.

One interesting result of the study was that a number of parameters had little or no impact on the MOEs. Table 40 summarizes the tested parameters that had no effect on the MOEs.

As table 40 shows, lane changing parameters were the majority of the parameters with no sensitivity. In fact, 11 of the 15 lane changing parameters in NETSIM showed no sensitivity. These nonsensitive parameters should be the focus of further research, because it is not clear why many of them did not have a greater impact on the MOEs. However, this study does not prove that these parameters have no sensitivity whatsoever. Testing different networks or using different MOEs could reveal additional sensitivity not discovered in this study. For example, examining more disaggregate MOEs, such as vehicle trajectory data, could reveal sensitivity of the parameters at a level which is not possible with aggregate MOEs, such as average speed over an entire link. The fact that most of these lane changing parameters had at least some small impact on the number of lane changes shows that the parameters were affecting traffic operations to some degree.

Table 40. Traffic Parameters with No Effect on MOEs.

Parameter Category	Parameter
FRESIM	
Car following	- Car following sensitivity factor - Jerk value
Lane changing	- Advantage threshold for discretionary lane change - Discretionary lane change multiplier - Gap acceptance parameter - Percent cooperative drivers
NETSIM	
Car following	- None
Lane changing	- Driver type factor - Urgency threshold - Headway at which all vehicles attempt a lane change - Headway at which no vehicle attempt a lane change - Difference in min/max deceleration for mandatory lane changes - Difference in min/max deceleration for discretionary lane changes - Safety factor - Duration of a lane change - Percent drivers who cooperate with a lane changer - Distance over which drivers perform a lane change - Distribution of distance to attempt a lane change
Discharge headway	- Discharge headway multiplier
Startup lost time	- Startup lost time multiplier
Turning speed	- None

In addition to the nonsensitive parameters, a number of FRESIM lane changing parameters had an "inconsistent" impact on the MOEs, named so because they had no consistent impact on the MOEs. These inconsistent parameters included the maximum non-emergency deceleration, maximum emergency deceleration, leader's maximum deceleration as perceived by follower, anticipatory lane change distance, and anticipatory lane change speed. These parameters should also be the focus of more detailed research to further determine how they function within the various model algorithms and exactly what impact they have on traffic operations.

Table 41 summarizes those parameters that had both an expected effect on the MOEs and were categorized as either having a medium or high effect on the MOEs (relative to the other parameters). This table is important because it identifies the key weather-related driver behavior parameters that should be altered when trying to model weather events in CORSIM. As stated earlier, this study does not recommend specific values to use for these parameters during various weather events, but it does identify these parameters as the most sensitive, and therefore should be the focus when calibrating a model for a specific weather event. A traffic analyst should first focus on the parameters with a high sensitivity level, and if further calibration is needed, could use those with a medium sensitivity level.

Table 41. Traffic Parameters with Expected and Medium-to-High Effect on MOEs.

Parameter Category	Parameter
FRESIM	
Car following	- *Car following sensitivity multiplier (high)* - Pitt car following constant (medium) - Lag acceleration/deceleration time (medium)
Lane changing	- Time to complete lane change (medium)
Free-flow speed	- *Mean free-flow speed (high)*
NETSIM	
Car following	- *Time to react to sudden deceleration of lead vehicle (high)*
Lane changing	- *Time to react to sudden deceleration of lead vehicle (high)* - Minimum deceleration for a lane change (medium) - Deceleration of lead vehicle (medium) - Deceleration of following vehicle (medium)
Free-flow speed	- *Mean free-flow speed (high)*
Discharge headway	- *Mean discharge headway (high)*
Startup lost time	- *Mean startup delay (high)*
Turning speed	- Maximum allowable left-turn speed (medium) - Maximum allowable right-turn speed (medium)

Note: Values in parenthesis (high, medium, or low) represent the sensitivity level of the parameter, with a parameter in italics representing a high sensitivity level.

Due to the large number of networks and variables tested in the sensitivity study, a number of additional findings and recommendations were made that were somewhat unrelated to the task of determining the most sensitive parameters, but nonetheless were thought to be important for CORSIM users in general. These findings can be summarized as follows:

- The minimum separation for generation of vehicles parameter is useful in calibrating the capacity of basic freeway segments, but users should realize that changing the driver behavior parameters (specifically the car following sensitivity multiplier) also can limit the freeway capacity in some cases.
- The minimum separation for generation of vehicles parameter is available only on freeways (FRESIM) and not on surface streets (NETSIM). As a result, arterial volumes up to 2700 veh/h/lane can be modeled in NETSIM, which is not realistic for arterials. However, the capacity will likely be limited by traffic signals on arterials, but nevertheless, traffic analysts should be careful to model realistic traffic volumes on arterial streets.
- In FRESIM, the maximum emergency deceleration and leader's maximum deceleration as perceived by follower parameters are identical parameters, as they produced exactly equal results in the sensitivity analysis.
- Changing the distribution of speeds for the free-flow speed multiplier is not recommended, because this produced inconsistent (and unrealistic for a distribution with very low standard deviation) impacts on the MOEs. In addition, changing the distribution of discharge headways and startup delays in NETSIM also is not recommended, because altering them had no effect on the MOEs.

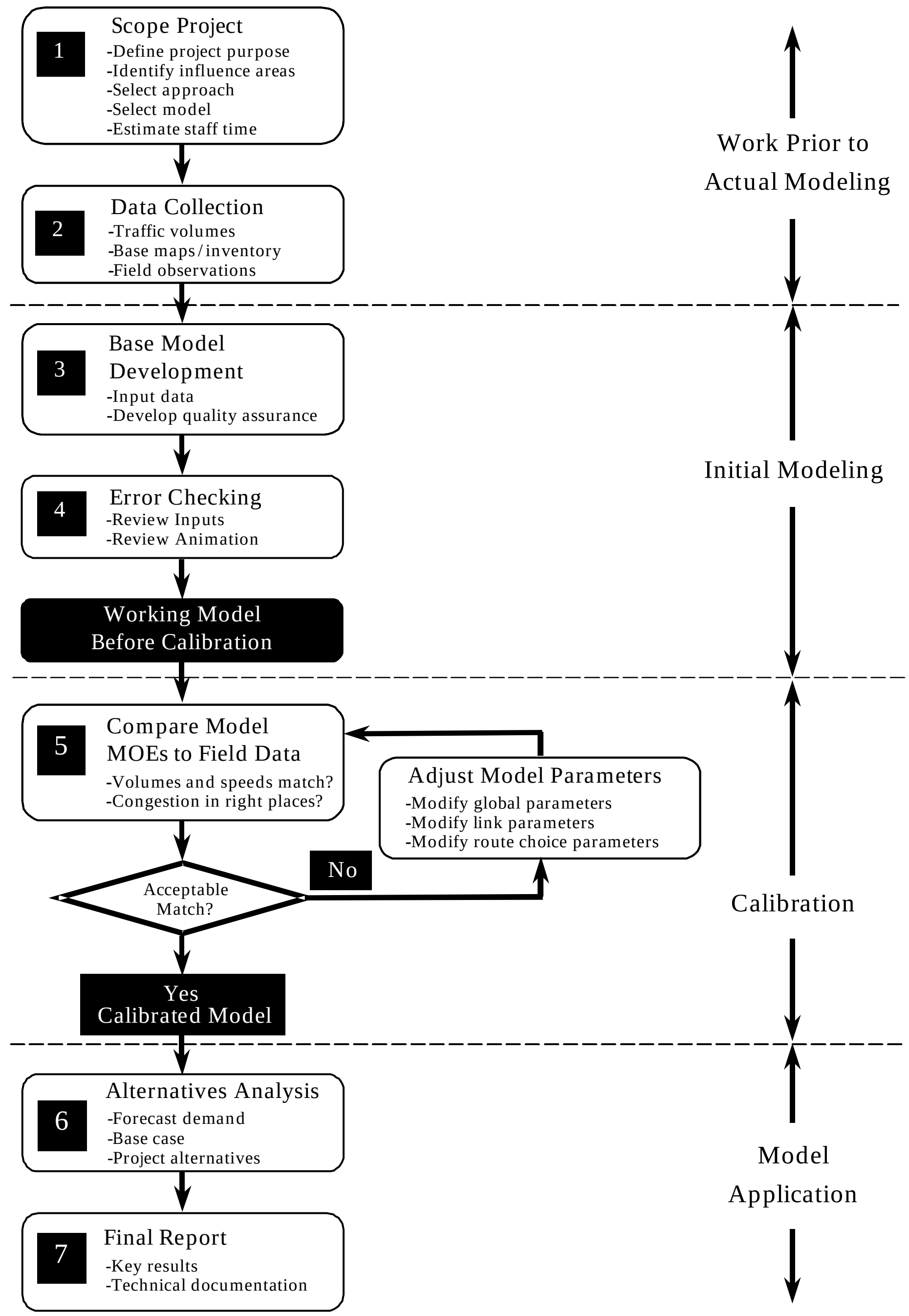
- Future consideration should be given to widening the allowable range for the deceleration of lead vehicle and deceleration of following vehicle parameters, given that they are two of the four NETSIM lane changing parameters that have a quantifiable impact on MOEs. Currently, the allowable range is 3.05 to 4.57m/s/s, with a default value of 3.66 m/s/s. The allowable range for the Pitt car following constant should also be widened (currently 0.91 to 3.05 m with a default value of 3.05 m) to at least 4.57 m to allow users to model more conservative car following behavior.
- The HCM recommends a default mean startup delay of 2.0 s, which is defined as the extra time consumed by the first few vehicles in a signalized intersection queue. In the absence of localized field data, it is recommended that CORSIM users use this value of 2.0 s, which means the default mean startup delay value should be changed to 1.3 s (currently 2.5 s), because 0.7 s of startup delay is already hard-coded into the model for the second and third vehicles in the queue.

6. Guidelines for Modeling Weather Events in CORSIM

This section provides practical guidelines for modeling the effects of adverse weather on a roadway network using CORSIM. The guidelines presented here are based on *Traffic Analysis Toolbox Volume III—Guidelines for Applying Traffic Microsimulation Modeling Software,* an FHWA guidance document on the development and application of microsimulation models.(1) Figure 13 shows the seven-step process recommended in the guidelines for developing a microsimulation model and how to apply the model to analyze various alternatives.

Even though the process shown in figure 13 was not designed specifically for modeling weather events, a traffic analyst intent on modeling weather effects should not forget the importance of scoping the project, collecting field data, developing the base model, checking the model for errors, calibrating the model to local conditions, analyzing alternatives, and producing a final report.

Figure 13 lays the foundation for developing and applying an accurate and valid CORSIM model. The same basic steps shown in this figure should be followed even when including the impacts of adverse weather. However, there are a few steps in the process that a traffic analyst should approach slightly differently when modeling adverse weather in CORSIM. These differences are highlighted in the remainder of this section.



Developed by the FHWA Traffic Analysis Tools Team and later adapted from *Advanced Corsim Training Manual*, Short, Elliott, Hendrickson, Inc., Minnesota Department of Transportation.

Figure 13. Microsimulation Model Development and Application Process.[1]

Step 1—Scope Project

It is important to define the project scope in any application of a microsimulation model. However, when using the model to include the effects of adverse weather, a few additional considerations are necessary, including:

- Does the selected microsimulation software package have an adequate number of weather-related parameters (see tables 2 through 6) that can be adjusted appropriately to model the weather impacts accurately?
- What type of weather event(s) will be modeled (e.g., snow, rain, fog, sun glare, or some combination)?
- What is the severity of the weather event(s) being modeled (e.g., 50 millimeters or 1 meter of snow)?
- What is the duration of the weather event(s) being modeled (e.g., will it last the entire simulation period, or just for a short period)?
- What is the extent of the weather event(s) being modeled (e.g., will it cover the entire simulation model area, or just a portion)?

These are important questions that should be answered and agreed on by all parties involved with developing and reviewing the model before beginning the actual model coding. The first question listed may be the most important of the entire project, because it determines whether the selected software package is able to include the effects of adverse weather successfully. The previous sections of this report have shown that CORSIM can be applied successfully to model weather events and generally does have adequate parameters to account for most weather events.

Step 2—Data Collection

Collecting actual roadway conditions in the field is important in any application of a microsimulation model. Typical data collected includes traffic volumes, roadway geometrics, signal timing data, transit and pedestrian data, and calibration data (or MOEs) such as capacities, travel times, intersection delays, and queue lengths. When modeling the effects of adverse weather, it is important to attempt to collect data during the weather events being modeled. For example, if the capacity and delay at an intersection is collected during heavy rain, those values obtained can be used to better calibrate a model taking into account heavy rain.

In addition to calibration data (MOEs), traffic parameter data (inputs to the traffic model) also are important to collect in the field during the weather events being modeled. Key weather-impacted traffic parameters identified both in this sensitivity study and the literature review include free-flow speed, car following sensitivity multiplier, discharge (saturation) headway, startup delay, and traffic demand.

Collecting these data in the field and using them as inputs to the microsimulation model will provide a more accurate starting point when going through the calibration process (step 5 in figure 13).

It is recognized that resources and budgets often make it difficult to perform an exhaustive data collection effort for ideal weather conditions, let alone for adverse weather. However, it also should be recognized that the quality of data collection is proportional to the overall quality of the microsimulation model. Therefore, if including the impacts of adverse weather is important to the project, then serious consideration should be given to some form of data collection during the weather event(s) being modeled.

In light of this, if field data collection during the weather event(s) being modeled is not possible or practical, then traffic analysts could use the findings of past research (see section 3) as a starting point when altering traffic parameters to more accurately reflect weather events.

Step 3—Base Model Development

This step includes the initial setup and coding of the microsimulation model and inputting the data collected in the field into the model. When including a weather event in the model, the following additional steps are necessary during the base model development:

1. Identify which traffic parameters are impacted by the weather event.
2. Determine the appropriate values for these weather-impacted parameters either by (in order of preference):
    - Field data collection.
    - Findings of past research.
    - Engineering judgment.

For the first step, table 42 can be used to determine which CORSIM parameters are affected by weather events. This table was developed by matching the generic traffic parameters identified in tables 3 through 7 in section 4 of this report to specific CORSIM parameters. To use the table, a traffic analyst must first determine how the weather event being modeled impacts the roadway environment. Figure 2 of this report (section 2) displays which weather events impact the roadway environment.

As an example, suppose a traffic analyst wants to use CORSIM to model the effects of a heavy snowstorm (say four inches in an hour) on a local roadway network. From figure 2, it can be seen that a snow event (especially a heavy snowstorm) will likely cause a reduction in driver visibility and pavement friction, and the storm could block lanes or cover signs and pavement markings. The traffic analyst would make the final determination whether the modeled snowstorm should include blocked lanes and covered signs and pavement markings. Based on these roadway environment impacts, the traffic analyst would then use table 42 to determine specific parameters in CORSIM that may need to be altered due to the snowstorm.

Table 42. CORSIM Parameters Impacted by Weather Events.

Generic Traffic Parameter	Roadway Environment Impact	CORSIM Parameter(s)	Details
ROAD GEOMETRY PARAMETERS			
Pavement condition	Reduced pavement friction	Pavement condition	Available in FRESIM (freeways) only. Parameter creates an upper bound for the mean free-flow speed.*
Number of lanes	Blocked lanes	Number of lanes	Can reduce the number of lanes based on the weather event.
Lane width	Blocked lanes	Lane width	Available in NETSIM only. Only changes the graphical display and not traffic operations.
Lane taper length	Blocked lanes	None	No parameter for length or type of taper, but can reduce the length of deceleration/ acceleration lanes (in FRESIM) themselves as surrogate.
Shoulder width	Blocked lanes	None	No parameter for shoulder width in FRESIM or NETSIM.
TRAFFIC CONTROL AND MANAGEMENT PARAMETERS			
Traffic signal/ ramp meter	Reduced visibility	Forward sight distance	No parameter to reduce the visibility of a signal/meter itself. Forward sight distance parameter specifies sight distance from a stop line at a NETSIM intersection.
	Failed traffic control devices	Traffic signal/ ramp meter properties	Can change the control to all-way or two-way stop to simulate flash or blackout conditions. For ramp meter, can turn off the meter for specific time periods.
Roadway signs (regulatory, warning, traveler information)	Reduced visibility	Anticipatory lane change distance, off-ramp reaction point	No parameter specifically for reducing the visibility of a sign itself. Can change the anticipatory lane change distance and off-ramp reaction point as surrogates to seeing exit signs on freeways.
Surveillance detectors	Failed communications	Detector properties	Can delete detectors to simulate failed detector communications.
On-street parking	Blocked lanes	Curb parking	Can disallow on-street parking for specific time periods.
VEHICLE PERFORMANCE PARAMETERS			
Acceleration / deceleration capability	Reduced friction/stability	Acceleration tables	Can change acceleration tables, including maximum acceleration, using record type 173 of the CORSIM input file.
Turning radius	Reduced friction/stability	Minimum drawn radius of curvature	Only changes the graphical display and not traffic operations.
TRAFFIC DEMAND PARAMETERS			
Vehicle demand	All**	Entry volume and turning volume	Entry volumes for each entering link can be adjusted as appropriate, and turning volumes can be adjusted depending on the weather event.
Route choice	All**	Traffic assignment properties	Available in NETSIM only. Cannot change impedances for individual links to simulate weather events.

Table 42. CORSIM Parameters Impacted by Weather Events (continued).

Generic Traffic Parameter	Roadway Environment Impact	CORSIM Parameter(s)	Details
DRIVER BEHAVIOR PARAMETERS			
Car following	All**	See tables 11 and 18	See table 35 for key parameters.
Lane changing	All**	See tables 12 and 19	See table 35 for key parameters.
Free-flow speed	All**	Mean free-flow speed and multipliers	Mean free-flow speed on all affected links should be changed according to the weather event.
Discharge headway	All**	Mean discharge headway and multipliers	Mean discharge headway (at signalized intersections) should be changed according to the weather event.
Startup delay	All**	Mean startup delay and multipliers	Mean startup delay (at signalized intersections) should be changed according to the weather event.
Intersection gap acceptance	All**	Acceptable gap in oncoming traffic (AGOT), cross-street traffic acceptable gap (CSTAG)	Change AGOT for turns at a traffic signal (permitted left turns and right turns on red) and CSTAG for movements at stop signs.
Turning speed	All**	Maximum allowable left- and right-turn speed	Can change maximum left- and/or right-turn speeds in NETSIM.
Response to yellow interval	All**	Amber interval response	Defines the acceptable deceleration for a vehicle to stop at a traffic signal.

Notes: * - Check CORSIM manual for more details.[12]
** - All roadway environment changes could impact the parameter.

After the weather-impacted CORSIM parameters are selected from table 42, then the proper value for them must be determined. As mentioned previously, determining the appropriate values ideally should be done through field data collection. Given that this is often not possible and/or practical for some parameters, the correct parameter values could be estimated through the findings of past research. See section 3 of this report for a review of relevant past research. It is important to use only past research that was collected on roadway facilities, congestion levels, and other field characteristics similar to those being modeled. Finally, in the absence of field data collection and past research, engineering judgment can be used to estimate the correct parameter values. For example, it is difficult to collect lane changing parameter data in the field, and there are no past studies regarding lane changing behavior in adverse weather. Thus, in this case, changing the lane changing parameters to represent slightly more conservative driver behavior (as would likely happen in adverse weather) would probably be a reasonable choice based on engineering judgment.

While table 42 shows the range of traffic parameters impacted by weather events, it may not be possible or practical to change all of the impacted parameters for various reasons. With these limitations in mind, a handful of key traffic parameters have been identified, based on past research and the sensitivity study summarized in this report, to be the most important weather-impacted parameters in terms of their impact on MOEs. Even when resources and budgets are tight, these CORSIM parameters at a minimum should be altered to appropriate values when modeling weather events:

- Mean free-flow speed (freeways and arterials).
- Car following sensitivity multiplier (freeways).
- Mean discharge headway (signalized intersections).
- Mean startup delay (signalized intersections).
- Traffic demand, in terms of reduced demand during more severe weather events (freeways and arterials).

Step 5—Model Calibration

Model calibration is an iterative process where the model parameters are altered until the model results (MOEs) adequately match the field-measured MOEs. Calibration is needed, because the default parameter values often do not result in model MOEs close to those measured in the field. This is especially true when including a weather event in the model, because all microsimulation software packages assume ideal weather conditions in the default values.

Even after adjusting the weather-impacted parameters to appropriate values as described in the previous section, calibration is likely still needed to ensure the best model parameters are used. The *Traffic Analysis Toolbox Volume III—Guidelines for Applying Traffic Microsimulation Modeling Software* recommends a three-step calibration strategy:[(1)]

1. *Capacity calibration*—an initial calibration of the parameters related to capacity.
2. *Route choice calibration*—a calibration of the traffic demand and route choice parameters to better match volumes measured in the field.
3. *System performance calibration*—a final calibration of all parameters affecting the MOEs to better match the model-produced and field-measured system performance.

For each step, calibrating the global parameters (parameters that affect the entire microsimulation model) should be done first, while fine-tuning link-specific parameters as necessary should follow.

The key weather-related parameters as identified in the previous section are also the key parameters used to calibrate any CORSIM model, regardless if a weather event is being modeled. Thus, the process for calibrating a model that includes a weather event is not really different than calibrating a generic CORSIM model. Refer to the simulation guidelines for more detail on the calibration process.[(1)]

This section highlights the need to measure MOEs in the field, because there would be no basis to calibrate to if field MOEs were not measured. When including a weather event in the microsimulation model, the best way to calibrate such a model would be to collect field MOEs during the weather event being modeled. However, as stated previously, this can be difficult.

If field MOEs are not collected during the modeled weather event, then a secondary method for calibrating the weather-related model is possible. In this method, the first step is to calibrate the model during ideal weather conditions. This includes coding the microsimulation model for ideal weather and then calibrating the model to field MOEs collected during ideal weather. After developing a calibrated ideal weather model, then only the weather-related parameters would be adjusted to account for the adverse weather. The weather-related parameters would be adjusted based on the discussion in the previous section (i.e., adjustments based on field data, then past research, and finally, engineering judgment). While such an approach would not produce a model specifically calibrated to the weather event, it would at least produce a reasonably adequate adverse-weather model, because it was already calibrated to ideal weather, and only a few parameters were adjusted thereafter.

7. Conclusions

The objectives of this study were to identify how weather events impact traffic operations, assess the sensitivity of weather-related parameters in the CORSIM traffic microsimulation model, and develop guidelines for using the CORSIM model to account for the impacts of adverse weather conditions on traffic operations. This section highlights the major findings and conclusions reached from the analysis documented in this report. Also, future research needs were identified as part of this project and are summarized below.

Relationship Between Weather Events and Traffic Operations

Conceptually, it is easy to understand that a major weather event, such as a snowstorm, will lead to lower average speeds and higher delays. However, it is important to understand what this relationship is, or in other words, what causes a weather event to degrade traffic operations.

A weather event impacts traffic operations through a chain reaction: the event causes a change in the roadway environment (e.g., reduced visibility and pavement friction), which causes a reduction in traffic parameters (e.g., lower free-flow speeds and capacities), thereby degrading traffic flow (e.g., higher delays and lower average speeds).

The qualitative impacts of weather events are seen easily through this relationship, but the quantitative impacts have been historically difficult to measure for a number of reasons. For example, there are many shades of the severity of a weather event, and the impacts are different regionally (i.e., a snowstorm in Florida will have more impact than the same storm in Minnesota) and by time of year (i.e., a snowstorm at the beginning of winter will likely have more impact than the same storm near the end of winter after drivers have acclimated to the adverse weather).

Numerous past research studies have shown a quantitative link between various weather events and reduced free-flow speeds, saturation (discharge) headway, startup lost time, and traffic demand. This research shows a link between weather events and changes in traffic parameters; however, very little research has focused on the role of roadway environment impacts in causing the degradation in traffic parameters. This lack of information probably is due to the difficulty in understanding why motorists respond to a weather event (i.e., is a reduction in free-flow speed really due to a reduction in pavement friction or reduction in visibility?).

Microsimulation Parameters Affected by Weather Events

Past research has documented a number of traffic parameters that are impacted by weather events. However, many microsimulation parameters have not been measured empirically to behave differently during adverse weather.

Tables 3 through 6 show the traffic simulation parameters that are likely impacted by weather events (through a change in the roadway environment). The selection of these parameters was based on the range of simulation parameters identified in table 2, the literature review, and engineering judgment based on the concept that driver behavior becomes more conservative during adverse weather conditions. Unfortunately, there is currently no empirical research supporting the latter concept. Therefore, the table only lists the range of potential, not proven, simulation parameters that may be used to model adverse weather conditions in a simulation model. These simulation parameters may be used as a guide for traffic analysts when considering which parameters to adjust when modeling adverse weather.

CORSIM Sensitivity Analysis

The purpose of the sensitivity analysis was to identify the most sensitive weather-related parameters in CORSIM. Each test parameter was modeled on various geometric networks and congestion (volume) levels using the default value, then changing the value to represent incrementally more conservative driver behavior, as would occur under adverse weather. The MOEs produced by the default value were then compared to the MOEs produced with the changed parameter values to determine the level of sensitivity the parameter has on the MOEs.

Due to the large number of roadway networks, congestion levels, and parameters tested, approximately 45,000 individual CORSIM runs were completed. As a result, a largely automated process of creating the CORSIM input files and summarizing the output files was created specifically for this project.

One interesting result of the sensitivity analysis was that a number of parameters tested (19 total) had little or no impact on the MOEs. The majority of these were lane changing parameters. This finding does not mean they have no sensitivity whatsoever; rather, the finding shows no sensitivity to the aggregate-level MOEs used for this study. It is likely that more sensitivity would have been measured by using more disaggregate MOEs, or by evaluating trajectories of individual vehicles.

A number of weather-related parameters had an expected effect on the MOEs and were categorized as either having a medium or high effect on the MOEs (relative to the other parameters). These parameters are important because they represent the key weather-related parameters that should be altered when trying to model weather events in CORSIM. These parameters include:

- Mean free-flow speed (FRESIM and NETSIM).
- Car following sensitivity multiplier (FRESIM).
- Time to react to sudden deceleration of lead vehicle (NETSIM).
- Mean discharge headway (NETSIM).
- Mean startup delay (NETSIM).

Table 41 provides a more detailed list of the key weather-related parameters identified during the sensitivity analysis.

Guidelines for Modeling Weather Events in CORSIM

A set of practical guidelines for modeling weather events in CORSIM was developed as a result of the CORSIM sensitivity analysis. The guidelines are based on *Traffic Analysis Toolbox Volume III—Guidelines for Applying Traffic Microsimulation Modeling Software*, an FHWA guidance document on the proper development and application of microsimulation models.(1) The guidance builds on the more general microsimulation guidance by providing additional considerations when modeling weather events in CORSIM. For example, the type, severity, extent, and time period of the weather event being modeled should be agreed before coding the model.

The guidelines list CORSIM parameters to consider changing when modeling various weather events (see table 42). Also, an alternate method of calibrating a weather event model is presented when field data collection during adverse weather is not possible.

Future Research Needs

Based on the findings of this study, a number of areas of future research were identified that would improve the ability of CORSIM to model weather events and improve the base understanding of the relationship between weather events and traffic operations. The four identified areas of future research are:

1. Empirical data collection to improve base understanding of impact of weather events on traffic operations.
2. CORSIM enhancements for modeling adverse weather events.
3. Further study of "insensitive" CORSIM parameters.
4. Real-world case study of modeling weather events using CORSIM.

The first area, improving the base understanding of the weather event-to-traffic operations link, is the most important area of future research, because it will help analysts in all applications of traffic analysis models better understand the impacts of adverse weather on traffic operations. This study showed the most sensitive weather-related parameters in CORSIM and, as such, these parameters should be of high importance to collect during adverse weather. While the empirical data collection will help determine the true impact of adverse weather on traffic operations, it will not shed light on the impacts not measurable by video or roadway detectors, namely, the reason why drivers change their driving behaviors. For this reason, supplemental human factors studies should be initiated that would help explain the impact of the roadway environment on traffic operations (i.e., did a driver slow down because of a reduction in visibility, reduction in pavement friction, or a combination of both?).

The second area of future research deals with improving the ability of CORSIM to model the impacts of weather events. Some basic improvements to CORSIM that would help analysts improve how they model the impacts of weather events include:

- *Separation of free-flow speed and maximum speed*—Under adverse weather, drivers may not drive as fast as under ideal weather conditions. In the current version of CORSIM, to model the changes in weather conditions (e.g. sight distance reduction in fog), users must adjust the free-flow speed to slow down vehicles. However, delay and other MOEs are calculated based on free-flow speed. Therefore, a reduction in free-flow speed reduces the delay and causes undesirable MOE values. By separating the parameters of free-flow speed and desirable maximum speed, analysts will be able to decrease the desirable maximum speed parameter while allowing the appropriate MOEs to be based on the free-flow speed.
- *Adequate consideration of roadway geometry*—CORSIM can account for a number of roadway geometry parameters that influence MOEs, but there are many others that are not taken into account that become more pronounced in adverse weather. Improving the CORSIM model to account for geometric features such as forward and lateral sight distance, horizontal and vertical curvature and alignment, and lane and

shoulder width would allow analysts to better analyze the full range of impacts of adverse weather.

- *Network vs. link-level parameters*—Currently, some CORSIM parameters are network-wide, and all individual links must use these network parameters. With the ability to model large networks in CORSIM and the isolated nature of some weather effects (i.e., shoulder blocked by a snow bank), it may be beneficial to have certain parameters associated with each individual link, such as gap acceptance parameter, lag acceleration/deceleration time, maximum emergency deceleration, percent cooperative drivers, time to complete lane change, Pitt car following constant, and car following sensitivity factor.

The third area of future research identifies the need for further study on 19 parameters that showed no or low sensitivity during the sensitivity study. The majority of these were lane changing parameters. An analysis of more disaggregate level MOEs would define further exactly what impact these parameters have on traffic flow during specific ranges of volume levels and network geometries.

The fourth area of future research comprises initiating a case study using CORSIM to model a set of real-world roadway networks under adverse weather. Such a study would showcase the state-of-the-art in modeling weather and traffic events, serve as a test of the guidelines developed in this study for applying a microsimulation model during adverse weather conditions, and discover shortcomings in the process that need further refinement or study. The case study ideally would be done at a number of locations with varying roadway geometries (such as on freeway sections and signalized arterials) and varying weather events (such as during light rain, heavy fog, and a major snowstorm).

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