Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-07/0-5278-1		

4. Title and Subtitle	5. Report Date
CONCEPTS FOR MANAGING FREEWAY OPERATIONS DURING WEATHER EVENTS	November 2006 Published: February 2007
	6. Performing Organization Code
7. Author(s) Kevin Balke, Praprut Songchitruksa, Hongchao Liu, Robert Brydia, Debbie Jasek, and Robert Benz	8. Performing Organization Report No. Report 0-5278-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-5278
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Technical Report: September 2005 – August 2006 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Managing Freeway Operations During Weather Events

URL: http://tti.tamu.edu/documents/0-5278-1.pdf

16. Abstract

The goal of this research was to help TxDOT develop a structured, systematic approach for managing traffic during weather events. Our focus in this research project was on common weather events – such as fog, high winds, heavy rains, and snow and ice storms – that impact traffic operations day-to-day. First, we conducted a survey of selected Texas Department of Transportation (TxDOT) districts to determine what information traffic management center (TMC) operators need to manage traffic operations during weather events. Through a review of the existing literature, we assessed systems and technologies that other states have deployed to manage traffic during weather-related events. We reviewed the current state of weather-related detection and monitoring technologies. Using historical traffic detector and weather information, we assessed the magnitude of the impact of different weather events on traffic operations. Using all this information, we developed concepts of operations for how TMC operators should respond to different types of weather-related events, including limited visibility conditions, ponding and flash flooding, high winds, severe thunderstorms, tornados, and winter storms. We developed a catalog of advisory, control, and treatment strategies (or *ACTS*) that operators could use to manage traffic operations during weather events. Specific criteria outline when TxDOT TMC operators should implement different types of responses. We proposed messages that TxDOT TMC operators can use on dynamic message signs (DMSs) to achieve different advisory and control strategies for different types of weather events. Finally, we provided a framework TxDOT can use to integrate weather information from the National Weather Service and other private weather providers into its TMC operations software.

17. Key Words	18. Distribution Statement
Concept of Operations, Freeway Operations, Weather	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	182	

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

CONCEPTS FOR MANAGING FREEWAY OPERATIONS DURING WEATHER EVENTS

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Report 0-5278-1
Project 0-5278
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Performed in cooperation with the
Texas Department of Transportation
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Federal Highway Administration

November 2006
Published: February 2007

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Kevin N. Balke, P.E. #65529, Texas.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The research team would like to acknowledge the leadership efforts of Mr. Carlos Chavez, P.E., Director of Transportation Operations, TxDOT – El Paso District, who served as the Project Coordinator, and Mr. Mike Taylor, P.E., Operations Manager, TxDOT – Amarillo District, who served as the Project Director for the project. The research team would also like to thank Mr. Gilbert Jordan, (TxDOT – El Paso District), Mr. John Gaynor, P.E. (TxDOT – Houston District), Ms. Molli Choate (TxDOT – Wichita Falls District), Mr. Victor De La Garza (TxDOT – El Paso District), and Mr. Darren McDaniel, P.E. (TxDOT – Traffic Operations Division) – all of who devoted their time and energies to making this a successful project by serving on the Project Advisory Committee. Finally, the research team would also like to express their sincere gratitude to Mr. Wade Odell, P.E., and Ms. Sandra Kaderka with the TxDOT Research and Technology Implementation Office for providing technical and administrative support throughout the project.

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INTRODUCTION

BACKGROUND

Weather events affect traffic on every roadway in the nation and have concerned transportation agencies for many years. Some weather events can disrupt access to freeways and damage roadway infrastructure. Even minor weather events can cause slick pavement, reduce travel speeds, increase speed variability, increase delay, and increase the potential for crashes. Many states, including Texas, are implementing weather monitoring systems to help prepare for inclement weather and operate the transportation system during major weather events. Weather events that cause the greatest concern to transportation officials are heavy rains and flooding, icing, dense fog, and high winds and dust storms. These types of events may cause either degradation of visibility or roadway conditions, or both.

Types of Weather Events

Transportation professionals generally group adverse weather events into five general categories: rain/flooding events, snow and icing events, events that cause low visibility (such as fog, blowing snow, or dust, etc.), high winds, and severe weather events *(1,2)*. Each of these events has its own set of characteristics that can affect traffic flow on a highway.

Although we talk about these events occurring in isolation from one another, it is not uncommon for two or more of the phenomena to occur simultaneously – for example, heavy rain coupled with high winds can reduce visibility to essentially zero.

Rain and Flooding

Rain causes wet pavement, which reduces vehicle traction and maneuverability. Heavy rain also reduces visibility distance. These impacts prompt drivers to travel at lower speeds causing reduced roadway capacity and increased delay. While rain events may not receive the same attention from the media as other types of weather events, rain can often have just as severe an effect on traffic operations. One potential reason rain events do not receive the attention that snow or other types of events receive is that rain is more common than and not as much of a deterrent to travel as snow and freezing rain. But because rain events are more common, their impact on traffic operations is much more widespread.

Flooding reduces roadway capacity by limiting or preventing access to submerged lanes. Inland flooding, usually following the evolution of a tropical storm, has typically been the greatest source of fatalities, and caused the most damage to roadway infrastructure.

Snow and Ice

Over 70 percent of the nation's roads are located in snowy regions, which receive more than 5 inches (13 cm) average snowfall annually. Nearly 70 percent of the U.S. population lives in these snowy regions. Snow and ice reduce pavement friction and vehicle maneuverability, causing slower speeds, reduced roadway capacity, and increased crash risk.

With the exception of the High Plains and West Texas regions, snow and ice events are relatively rare in Texas; however, this does not mean that their effects can be ignored. Because they do not occur with regular frequency, most drivers in Texas are not well-practiced in driving in these conditions. When these events do occur, they can have crippling effects on transportation in these regions. West Texas and High Plains regions of Texas can expect at least one major snow event per year that can make travel hazardous even for the most practiced and well-prepared drivers.

Low Visibility

Visibility distance is reduced by fog and heavy precipitation, as well as wind-blown snow, dust, and smoke. Low visibility conditions cause increased speed variance, which increases crash risk. Because of the low annual average rainfall amounts, portions of West Texas and the High Plains experience sand and dust storms with regular frequency. Fog is a common problem in the Gulf Coast and East Texas regions.

High Winds

High winds reduce roadway capacity by obstructing lanes or roads with drifting snow and wind-blown debris, such as tree limbs. Wind-blown snow, dust, and smoke can impact mobility by reducing visibility distance. High winds can also impact the stability of vehicles, particularly high-profile vehicles.

Severe Events

Hurricanes are perhaps the largest type of severe storm that can affect Texas, especially the Gulf Coast region. Hurricanes form in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico, and can travel thousands of miles before dissipating. If the right conditions last long enough, a hurricane can produce violent winds, incredible waves, torrential rains, and floods. There are, on average, six Atlantic hurricanes each year; over a 3-year period, approximately five hurricanes strike the U.S. coastline from Texas to Maine. One of the most damaging features of these storms is the storm surge, which when coupled with torrential rainfall amounts, can cause severe flooding well inland from the coast. Heavy rains associated with these storms can travel far inland. When hurricanes move onto land, the heavy rain, strong winds, and heavy waves can damage buildings, trees, and cars (*3*).

Tornados are another common type of severe weather event that can occur in Texas. A tornado is a violently rotating column of air extending from a thunderstorm to the ground. The most violent tornados are capable of tremendous destruction with wind speeds of 250 mph or more. Damage paths can be in excess of 1 mile wide and 50 miles long (*4*). What makes tornado events particularly dangerous is that they can occur with little or no warning. Although tornados can occur anywhere in Texas, the High Plains and Central Texas are most susceptible to tornado events.

Weather Impacts on Safety and Operations

Table 1 and Table 2 show the impact of weather events on the number of crashes, fatalities, and injuries occurring in 2001 in the United States (*5*). These tables show that most weather-related crashes occur on wet pavement and during rainfall. In fact, nearly 79 percent of all weather-related vehicle crashes in the United States occurred on wet pavement and nearly 49 percent happened during rainfall (*5*).

Table 1. Condition of Pavement for 2001 Weather-Related Crashes in the United States.

Pavement Conditions	Number of Crashes	Fatalities	Injuries
Snowy/slushy	110,072	1,100	95,000
Wet	1,100,000	5,400	511,000

Source: *Analysis of Weather-Related Crashes on U.S. Highways (5)*.

Table 2. Weather-Related Crashes by Event Type – Total for the United States in 2001.

Event Type	Number of Crashes	Fatalities	Injuries
Rainfall	688,304	3,200	309,000
Snowfall	183,377	790	62,000
Fog	43,792	670	19,000

Source: *Analysis of Weather-Related Crashes on U.S. Highways (5)*.

While specific data are not available for Texas, it is logical to assume that weather-related events have a similar impact on traffic safety in Texas.

According to the Federal Highway Administration (FHWA), adverse weather is the second largest cause of non-recurrent congestion (*1*). Snow, ice, and fog contribute significantly to the total amount of non-recurring delays in an urban area – 15 percent of non-recurring delays can be attributed to these events. Even light rain can increase travel time delay by 12 to 20 percent. These increases in delay and travel time can have a direct financial impact on users in an area. For example, freight operators lose about $3.4 billion (about 32 million hours) stuck in weather-related traffic delays in metropolitan areas. A one-day highway shutdown can cost a metropolitan area up to $76 million in lost time, wages, and productivity.

Weather can also have a significant impact on both speeds and capacity of a freeway. The effects of rain and snow on freeway free-flow speeds and capacity are shown in Figure 1. According to the *Highway Capacity Manual* (*6*), light rain or snow can reduce free-flow speeds by approximately 6 mph. In heavy rain, the reduction in free-flow speeds doubles – approximately a 12 mph reduction in free-flow speeds. These reductions equate to drops in capacity of approximately 4 and 9 percent, respectively.

Heavy snow events have a much greater impact on speeds and capacity. Snow accumulations can obscure lane markings and increase driver uncertainty, particularly if snowclearing operations cannot keep pace with the snow accumulations. Drivers increase their headways, reduce their travel speeds, and increase their lateral clearance. It is not uncommon for a three-lane freeway to operate as if it had only two widely separated lanes during snow events. In fact, the *Highway Capacity Manual* indicates that a 31 mph reduction in free-flow speeds and a 30 percent reduction in capacity are common in major snow events.

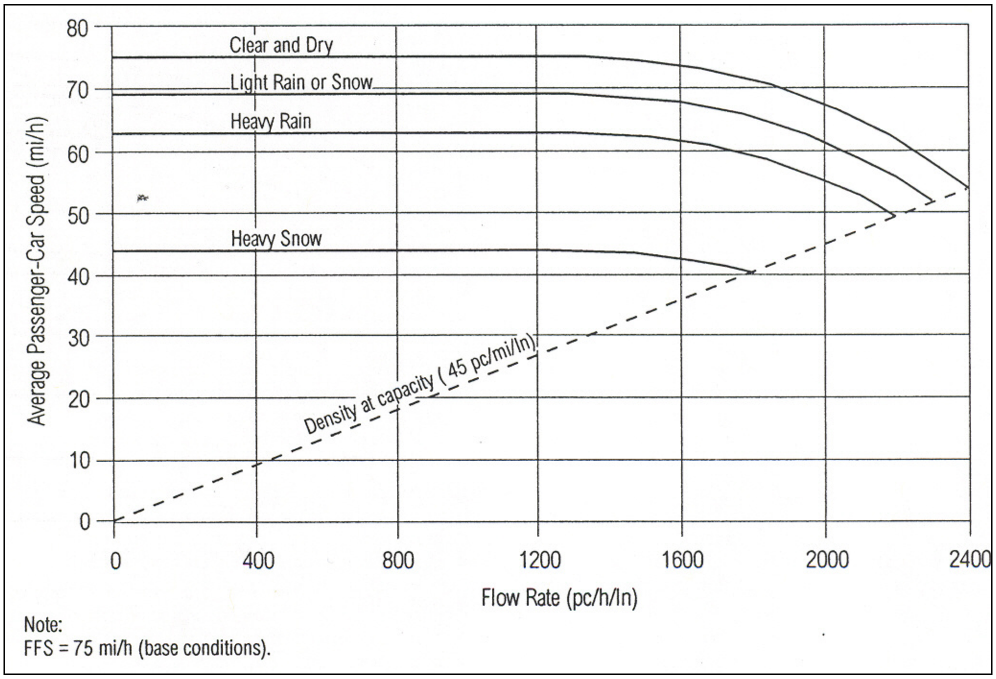


Figure 1. Effects of Different Weather Conditions on Speed-Flow Relationship (*6*).

PROJECT GOALS AND OBJECTIVES

The goal of this research is to help TxDOT develop a structured, systematic approach for managing traffic during weather events. This research provides answers to the following questions:

- What data, processes, and procedures does TxDOT need to support weather-responsive traffic management?
- How should weather-related data, processes, and procedures be integrated with TxDOT's current traffic management systems and activities?
- What additional resources does TxDOT need to support weather-responsive traffic management?

The Texas Transportation Institute (TTI) and Texas Tech University (TTU) have joined forces and developed the work plan listed below to provide TxDOT with the answers to these questions.

The scope of this research project was focused specifically on the following four weather events:

- snow,
- rain/flooding,
- high winds, and
- low visibility (fog, blowing sand/snow, etc.).

The research team divided to focus on specific events more relevant to their particular region. Because snow events are much more prevalent in the Panhandle and West Texas regions of Texas, TTU led the exploration of issues related to snow events, while TTI took the lead on efforts examining events involving rain, low visibility, and high winds. Because multiple situations and circumstances often occur with a single weather event (e.g., there may be high winds associated with a snow event causing blowing snow to reduce visibility), the project team coordinated its efforts to ensure that all traffic management aspects of an event were also coordinated.

ORGANIZATION OF REPORT

This report contains eight major sections. The first section (this section) provides an overview and background for the project. In the next section, we present the results of a survey of selected TxDOT districts to determine what information traffic management center (TMC) operators need to manage traffic operations during weather events. In the third section, we provide an assessment of some of the systems and technologies that other states have deployed to manage traffic during weather-related events. Following that section, we have a fourth section that provides a review of the current state of weather-related detection and monitoring technologies. In the fifth section, we show the results of an analysis we did to assess the magnitude of the impact of different weather events on traffic operations using historical weather and traffic data. Section six provides the concepts of operations we developed for how TMC operators should respond to different types of weather-related events, including limited visibility conditions, ponding and flash flooding, high winds, severe thunderstorms, tornados, and winter storms. We have also in section seven developed a catalog of advisory, control, and treatment strategies (or *ACTS*) that operators could use to manage traffic operations during weather events. We have proposed messages that TxDOT TMC operators can use on dynamic message signs (DMSs) to achieve different advisory and control strategies for different types of weather events. In the final section we propose a framework that TxDOT can use to integrate weather information from the National Weather Service and other private weather providers into its TMC operations software.

IDENTIFICATION OF TXDOT WEATHER INFORMATION NEEDS

One objective of this research project was to identify and assess the information needs and requirements of the TxDOT personnel involved in managing traffic during a weather event. The specific purpose of this task was to gain insight into the following questions:

- What information does a TxDOT operator in a traffic management center need to better operate the freeway system during major weather events?
- If TxDOT operators had access to this information, how would they use the information to operate the system differently?

SURVEY OF SELECT TXDOT DISTRICTS

To obtain this insight, the project team conducted site visit interviews with operations and maintenance personnel in several TxDOT districts. We developed a form to aid the researcher in asking consistent questions at each of the interviews and to provide a mechanism for recording responses. This form is contained in Appendix A. We conducted site interviews in the following districts: Pharr, Corpus Christi, El Paso, Lubbock, Amarillo, Wichita Falls, and Houston.

In addition to these "formal" interviews, the research team conducted several "informal" interviews where, during the course of normal correspondence and discussion, we asked TxDOT personnel about information needs and strategies for managing freeway operations during weather events. The results of these discussions are also incorporated in the findings below.

All of the TxDOT districts surveyed reported that significant weather events affected traffic operations within their districts. Table 3 shows the frequency at which different types of weather events occur in each of the surveyed districts. As seen from Table 3, regional differences clearly exist in Texas, with the southern districts experiencing more problems with dense fog and rainfall than the northern districts, and the northern districts experiencing winter weather events (such as snow and icing) more frequently than southern districts. When the research team asked which events were most prevalent in their districts, two districts reported dense fog as their most prevalent event, four districts reported high winds being their most significant event, and one district reported flooding roadways as its most prevalent event. Again, we found that the survey responses were clustered by regions within the state.

Table 3. Frequency of Weather Events Reported by TxDOT Districts.

Type of Weather Event	TxDOT Districts						
	Pharr	Corpus Christi	El Paso	Lubbock	Amarillo	Wichita Falls	Houston
Snowfall	Rarely	Rarely	Rarely	≥ 4 times per year	≥ 4 times per year	1 – 2 times per year	Once every 3 – 5 years
Icy Roads	Rarely	1 – 2 times per year	1 – 2 times per year	≥ 4 times per year	≥ 4 times per year	2 – 4 times per year	Once every 3 – 5 years
Dense Fog	≥ 4 times per year	≥ 4 times per year	Rarely	≥ 4 times per year	≥ 4 times per year	1 – 2 times per year	2 – 4 times per year
Dust Storms	Rarely	Rarely	1 – 2 times per year	≥ 4 times per year	1 – 2 times per year	Once every 1 – 2 years	Rarely
High Winds	≥ 4 times per year	≥ 4 times per year	≥ 4 times per year	≥ 4 times per year	≥ 4 times per year	≥ 4 times per year	Once every 3 – 5 years
Tornados	Rarely	Once every 1 – 2 years	Rarely	≥ 4 times per year	2 – 4 times per year	2 – 4 times per year	Once every 1 – 2 years
Flash Floods	Once every 1 – 2 years	Rarely	1 – 2 times per year	≥ 4 times per year	Once every 1 – 2 years	Once every 1 – 2 years	≥ 4 times per year
Floods from Rising Water	Once every 1 – 2 years	1 – 2 times per year	Rarely	≥ 4 times per year	Once every 1 – 2 years	1 – 2 times per year	≥ 4 times per year

When asked if weather impacted traffic safety, all of the districts reported that weather could significantly impact traveler safety. Table 4 shows how the various districts responded to this question.

The research team also asked what type of special traffic management techniques were used by the districts prior to, during, and after a weather event in their districts. Table 5 shows the current range of techniques used by TxDOT to manage traffic operations during weather events. Most districts use DMSs or other types of signing techniques to provide travelers with advance notification of potential hazardous travel conditions caused by weather events. Table 6 shows how the districts responded when asked what issues impact traffic operations after a weather event in their districts. Clearly, rapid debris removal and restoring roadways to their full operating capacity were the most urgent issues facing TxDOT after a weather event.

Table 4. Survey Responses as to How Weather Events Affected Daily Traffic Operations.

District	Survey Responses
Pharr	Yes, especially in the South Padre area. Winds blow dune sand onto road, winds affect high-profile vehicles on Queen Isabella Causeway.
Corpus Christi	Yes rising water creates roadway hazard, dense fog can hamper travel conditions, safety on bridges, and in work zones.
El Paso	Yes.
Lubbock	Problem with work signs blowing down, and material moving off target, such as herbicide operations, asphalt during seal coat aggregate blowing away from intended area, safety concerns for maintenance personnel.
Amarillo	Not much.
Wichita Falls	Yes, because of elevated roadway section through town, high winds could affect the safety of traffic on these routes.
Houston	Yes, traffic detours traffic congestion.

Table 5. Summary of Types of Measures Used by TxDOT District prior to or during a Weather Event.

District	Survey Responses
Pharr	Yes – traveler warnings are put out on DMSs. If winds reach 45 mph, the Queen Isabella Causeway bridge is closed to high-profile vehicles. If fog, a dense fog warning message is sent.
Corpus Christi	Yes – traveler warnings are put out on DMSs. If there is rising water, barriers are put out. If there is ice, sanding bridges is required.
El Paso	Yes – traveler warnings are put out on DMSs. If there is ice, sanding bridges is required. If there is rising water, barriers are put out.
Lubbock	Secure road work signs on projects.
Amarillo	None.
Wichita Falls	Special maintenance and operations measures are required. Danger to the traveling public must be established through current weather sensor.
Houston	Not many. Primarily warnings about icy roads.

Table 6. Summary of Types of Actions Used by TxDOT Districts after a Weather Event.

District	Survey Responses
Pharr	Yes – high winds on the island often blow dune sand onto the road and the roadway has to be cleared.
Corpus Christi	N/A
El Paso	N/A
Lubbock	Remove debris and sand off roadway, replace damaged signs.
Amarillo	Yes, there are many small signs that have been blown over or damaged and need to be replaced.
Wichita Falls	N/A
Houston	Cleanup and removal; vehicle removal; pavement repairs.

The research team also asked each district if they thought that having additional weather information would influence their decision-making process. Four districts indicated that having more information would help improve their decision-making, while three districts indicated that it would not. When asked about how much lead-time was needed in order for districts to maximize their effectiveness, all but one of the districts indicated that less than 4 hours advance notification was required. One district reported that, depending upon the event, as little as 30 to 45 minutes advance notification would be sufficient to allow them to do a better job at operating their facilities. Most TxDOT districts indicated that the weather information needed to be localized to the specific feature of concern. When asked about the required level of accuracy of the information, most TxDOT districts agreed that the level of accuracy needed to be high in order to be useful to district personnel in making decisions that impacted traffic operations. Table 7, Table 8, and Table 9 provide the replies received in response to questions about timeliness, specificity, and accuracy of needed weather information.

The research team also asked each district to assess the road weather information devices currently deployed in their district. Table 10 shows how each surveyed district responded to questions concerning the devices used to obtain road weather information. Generally, all but one of the districts felt that their devices work relatively well, and were positioned correctly. Several of the districts indicated that they felt that the information provided by the devices being used was not reliable or accurate. Because of these issues, these districts felt that they could not use these devices to assist them in making operational decisions.

Table 7. Summary of Responses Related to the Required Advance Warning Time of Weather Events.

District	Survey Responses
Pharr	1 to 2 hours
Corpus Christi	4 hours
El Paso	3 to 4 hours
Lubbock	Normally, 24 hours notice would be sufficient to adjust daily work schedules if it was a given that a major wind storm was approaching.
Amarillo	N/A
Wichita Falls	N/A
Houston	30 to 45 minutes

Table 8. Summary of Responses Related to the Required Level of Specificity of Weather Information.

District	Survey Responses
Pharr	It needs to be specific to island area and causeway area, especially on wind speeds.
Corpus Christi	As localized as possible would be helpful (down to county area).
El Paso	Regional is OK; localized would be better.
Lubbock	Very specific. We can get the local forecast without any problems, but if we can pinpoint the severity and location of events that becomes useful information.
Amarillo	The information is already specific enough.
Wichita Falls	Currently we have weather sensors that give us wind information and we use the wind sensors and wind gust data but we have had times when we were not sure if the information was reliable. So, I would like to see a way to check to make sure information from sensor is correct.
Houston	Quadrant of city; corridor 8 to 10 mile range.

Table 9. Summary of Responses Related to the Required Level of Accuracy of Weather Information.

District	Survey Responses
Pharr	Fog formation and wind speeds.
Corpus Christi	Any information about weather in outlying areas would be good. There is usually enough information about Corpus proper. It is the outlying areas of the district we need information on.
El Paso	Any early warning would help.
Lubbock	24-hour advance notice with 99.9% assurance that the event will take place.
Amarillo	We currently receive enough information to deal with the weather event.
Wichita Falls	N/A
Houston	Magnitude and duration; some forecasters doing that now.

Table 10. Assessment of Devices Used to Obtain Road Weather Information.

Assessment of Devices	TxDOT Districts						
	Pharr	Corpus Christi	El Paso	Lubbock	Amarillo	Wichita Falls	Houston
Does it work well?	Yes	Yes	–	No	Yes	Yes	Yes
Is it reliable?	Yes	Yes	–	No	Yes	No	Yes
Is it in the right location?	Yes	Yes	–	Yes	Yes	Yes	Yes
Does it provide the right information?	Yes	Yes	–	No	No	Yes	Yes
Do you use it to make operational decisions?	Yes	Yes	–	No	No	Yes	Yes

The research team also asked each district if they currently had documented plans for managing traffic operations during weather events. Two of the districts indicated that they currently had plans, and another one indicated they had a draft plan prepared but it was not yet finalized at the time of the survey. All of the other districts indicated that they currently did not have a plan but they had unofficial, informal response plans developed that they consistently applied during weather events.

SUMMARY OF WEATHER-RELATED INFORMATION NEEDS

Below is a summary of the TxDOT weather-related information needs from both the formal survey and informal discussion with the TxDOT districts:

- The types of weather events that TxDOT is concerned about vary greatly from region to region within the state. Gulf Coast districts are primarily concerned about heavy rains, flooding, and to a lesser extent limited visibility due to fog. These districts are also concerned with limited visibility during high intensity rainfall events. The Panhandle and North Texas districts are primarily concerned about winter weather events, such as snow and ice storms. Panhandle and West Texas districts occasionally have limited visibility issues caused by blowing dust or dust storms. Central Texas districts are primarily concerned with rain events that can cause flash flooding. Panhandle, North Texas, and to a somewhat lesser degree, the Central Texas districts are concerned about tornado events.
- High winds are a major issue primarily because of high-profile vehicles (i.e., tractor-trailer rigs or other vehicles that may have a high center of gravity and a "flat" panel side). In the Gulf Coast regions, districts are primarily concerned with high-wind events on overpasses or tall bridges. For the West Texas and Panhandle districts, high winds are an issue not only on bridges and overpasses, but on at-grade sections of freeways as well.
- Several districts have already developed either formal or informal procedures for managing traffic during weather events. For example, the El Paso District recently completed a traffic management plan for snow events. Many of the districts (such as the Amarillo District and the Wichita Falls District) have informal procedures in place for managing traffic during ice events. Other districts, such as the Houston District, are in the process of formalizing response and management procedures for other weather events, such as flooding events. All of the Gulf Coast districts have hurricane evacuation plans.
- Many districts currently have access to the National Weather Service's (NWS) Severe Weather Alert System or similar information in their control centers. In some cases, TMC operators, especially in the larger metropolitan areas, have access to better, more accurate information about weather events both prior to and as they are

occurring. While this information from the NWS is important to potentially alert operators to developing situations, the information contained in the alerts is often not specific enough to be used for traffic management purposes. Most districts require specific information as to when and where a weather event will impact a particular roadway (i.e., when a specific thunderstorm cell will reach a particular section of highway). Several districts indicated that alternative sources of weather information, such as local offices of emergency management (OEMs) and television/web-based forecasts, and local radar images, can provide this type of weather information.

- Several districts expressed the need to coordinate the dissemination of weather-related closures between other districts and, in some cases, between neighboring states. Several districts mentioned that they routinely display weather-related closures on dynamic message signs and websites. Guidance is needed as to when and under what conditions TxDOT operators should use dynamic message signs to disseminate weather-related information from other districts and states.
- One theme that consistently appeared as part of the discussion with the various TxDOT districts was the need for better coordination and communications not only between different agencies – the local OEMs, law enforcement/emergency response agencies, and departments of transportation (DOTs) – but also within TxDOT districts (i.e., between the District Traffic Operations office or TMC, and the maintenance sections and/or area offices). The maintenance section supervisors and/or area offices are generally responsible for entering and updating the status of weather-related road closures in the TxDOT Highway Condition Reporting System. However, when major weather events are occurring, the maintenance supervisors are often involved with getting personnel, equipment, and resources to the problem areas. Because they are often heavily focused in on "getting the job done," entering and disseminating weather-related roadway information to other users through this system could be delayed. To effectively manage freeway operations during weather events, TMC operators need to have access to information and should be provided with constant updates about weather-related road closures and situations as they occur.

ASSESSMENT OF THE USE OF WEATHER INFORMATION IN OTHER STATES

Almost every state displays or disseminates some type of weather or roadway condition information. Many states have deployed networks of road weather information system (RWIS) for the purposes of assessing travel conditions. Travelers can access this information through websites that contain information on the status of the roadway and current weather conditions. In addition to these types of systems, many agencies have also developed and implemented systems designed to manage traffic during weather events. The purpose of this section is to provide an overview of some of the technologies and systems that have been deployed in different parts of the United States for the specific purpose of managing traffic operations during weather events.

LIMITED VISIBILITY SYSTEM

Several states have developed and deployed systems specifically to manage traffic operations during limited visibility conditions (*7*). Most of these systems have been developed to address limited visibility situations caused by fog; however, much of the same technology and concepts can be applied to locales where smoke, blowing sand, and mist can create similar limited visibility conditions.

Sample Deployments

The discussion below represents a summary of the types of limited visibility systems that have been deployed in other states.

California

In 1996, District 10 of the California Department of Transportation (Caltrans) implemented the California Automated Warning System (CAWS) (*8*). The primary function of CAWS is to detect the presence of reduced visibility and/or congested traffic conditions, and to automatically activate motorist information systems to warn drivers of the conditions ahead.

The system includes the following:

- 36 traffic speed monitoring sites,
- 9 complete remote meteorological stations with visibility detectors, and
- 9 dynamic message signs.

The system is controlled by a network of three computers located in the District 10 Transportation Management Center. Caltrans Operations developed specialized software to activate the system.

Nine weather monitoring stations manufactured and installed by Qualametrics, Inc., were deployed along two major freeways in the Stockton-Manteca area. The stations were at 1 to 2 mile spacings. Each station included the following:

- a dual axis atmospheric visibility sensor,
- an anemometer,
- a barometer,
- a thermometer,
- a dew point sensor,
- a precipitation gauge, and
- a telemetry system for encoding and transmitting the data to a central facility.

Traffic conditions on the freeways are monitored using loop detectors installed in a speed detection trap arrangement. The traffic detection stations are spaced approximately at ½ mile intervals. Some of the traffic detector stations are located at or in the proximate vicinity to weather stations. Each traffic detection station is polled every 30 seconds. Speed measurements are averaged over a 15-minute sample interval. Average speed data are then aggregated into fixed-range increments for flow classification purposes.

A central processor installed in the TMC obtains visibility and speed information from the weather monitoring station and speed information. The processor compares both speed and visibility to established criteria. If the software detects that conditions exceed the established criteria, the system automatically posts warning messages on the dynamic message signs. Caltrans did not indicate how long these conditions had to persist before the system activated the DMSs. The criteria used to activate the signs are shown in Table 11.

Table 11. Criteria for Activating DMSs in California's Limited Visibility System.

Condition	Criteria	Message Displayed on DMS
Speed	< 35 mph	"SLOW TRAFFIC AHEAD"
	< 11 mph	"STOPPED TRAFFIC AHEAD"
Visibility	200 – 500 ft	"FOGGY CONDITION AHEAD"
	≤ 200 ft	"DENSE FOG AHEAD"
Wind	> 25 mph	"HIGH WIND WARNING"

The system uses a hierarchy in the posting of weather-related messages with the speed-related warning message superseding visibility and/or wind warnings. Information on the process used to deactivate the signs was not available.

Tennessee

Following a horrendous fatal accident on I-75 near Calhoun in December 1990, the Tennessee Department of Transportation (TDOT) implemented a fog detection and warning system on an 8-mile stretch of I-75 (*7*). The system was designed to warn motorists of hazardous driving conditions using a series of warnings and reduced speed limit signs. Travelers are warned of limited visibility and speed advisory conditions through a series of DMSs and highway advisory radios (HARs) deployed in the corridor.

The system has been designed to continuously monitor weather and visibility conditions in and around the fog-prone area. The system uses two meteorological monitoring stations and several backscatter visiometers to provide climatological and visibility information. TDOT has established a series of visibility thresholds for when different types of traffic management responses are to be triggered. When visibility falls below these thresholds, the operators respond by activating predetermined messages on some or all the dynamic message signs and highway advisory radios. When visibility gets to be less than 240 ft, the Highway Patrol activates eight automatic ramp gates that close the Interstate and detours traffic to an alternate route (US 11). Table 12 shows the messages used by TDOT when the system was activated.

Table 12. Messages Used by TDOT in Limited Visibility Conditions (9).

Conditions	Displayed Messages
Reduced Speed Detected	Flashing “CAUTION” with “SLOW TRAFFIC AHEAD”
Fog Detected	Flashing “CAUTION” with “FOG AHEAD TURN ON LOW BEAMS”
Speed Limit Reduced	Flashing “FOG AHEAD” with “ADVISORY RADIO TUNE TO XXXX AM”
	Flashing “FOG AHEAD” with “REDUCE SPEED TURN ON LOW BEAMS”
	Flashing “FOG AHEAD” with “SPEED LIMIT YY MPH”
Roadway Closed	Flashing “DETOUR AHEAD” with “REDUCE SPEED MERGE RIGHT”
	Flashing “I-75 CLOSED” with “DETOUR AHEAD”
	Flashing “FOG AHEAD” with “ADVISORY RADIO TUNE TO XXXX AM”

In addition to the weather monitoring station, TDOT has installed a series of 44 radar vehicle flow detectors on the approaches to and within the fog-prone area. Thresholds in changes of speed and/or flow monitored by the site computer automatically activate messages on the dynamic message signs and change speed limits on variable speed limit signs.

Georgia

The Georgia Department of Transportation, with the assistance of Georgia Tech University, has developed and deployed an automated adverse visibility warning and control system for a 14-mile stretch of I-75 in southern Georgia (*10*). This section of I-75 passes through a peat bog area where the combination of air temperatures and humidity cause fog to form frequently. The area also suffers from smoke accumulations due to agricultural burning during certain times of the year. The system became operational in 2001.

The system uses a total of 19 fog sensors spaced at approximately ¼ mile intervals in the fog-prone area. Five sets of loop detectors have also been installed in the corridor to measure speeds on the freeway. A weather station is installed in the fog-prone area to provide and log additional weather information. A processor unit installed in the middle of the corridor collects and processes the visibility and speed information from the field units, generates and posts warning messages, and activates another system for collecting evaluation data. The processor unit also notifies the local TMC that the message signs have been activated. Remote access capabilities have been built into the system to allow operators and administrators to access the processor unit to determine its status and the status of the dynamic message signs.

Four dynamic message signs (two in each direction) have been installed upstream of the fog-prone section to provide fog warning alerts and speed advisories through the section. The first dynamic message sign is installed 4 to 7 miles upstream and provides motorists with advance warning of the visibility conditions downstream. A second DMS has been installed approximately 1 mile upstream and provides updated speed advisory information as drivers enter the fog area.

The system has been configured to automatically generate messages for display on the dynamic message signs. The processor unit obtains visibility reading, speed measurements, and weather information from the field units once every minute. The processor obtains the visibility readings from all the detectors and computes the average visibility throughout the section. The average visibility measure is then compared to a series of thresholds to determine the suggested safe speed through the corridor. Visibility thresholds have been set at 1100 ft, 800 ft, 500 ft, and 300 ft. These visibility distances roughly correspond to the American Association of State Highway and Transportation Officials (AASHTO) recommended stopping sight distances for a 2-second perception and reaction time. (For example, the recommended stopping sight distance for traffic traveling at 70 mph, assuming a 2-second perception-reaction time, is approximately 800 ft.) The system uses the nomograph shown in Figure 2 to select an advisory speed.

The system also uses actual speeds to ensure that it does not post advisory speeds that are higher than those that currently exist in the section.

System Architecture

Most of the limited visibility warning systems that have been deployed in the United States tend to operate as stand-alone systems at isolated or specific locations where fog is a recurring problem. Being automated, most do not require an operator to assist in the decision-making process, but instead make control decisions and implement the messaging system directly in the field. In these automated systems, visibility sensors are generally deployed as part of an array of weather monitoring devices installed in conjunction with the system. With most systems, a central process extracts the amount of available visibility from the sensor and compares it to the established thresholds for the specific location. Some systems also use prevailing travel speeds in setting the speed advisories. These speed measures generally come from a typical traffic detection system that has been deployed as part of the limited visibility warning system. Dynamic message signs are generally used to provide the motorist with speed advisory and limited visibility warning messages. Figure 3 shows a system architecture diagram for a typical limited visibility warning system.

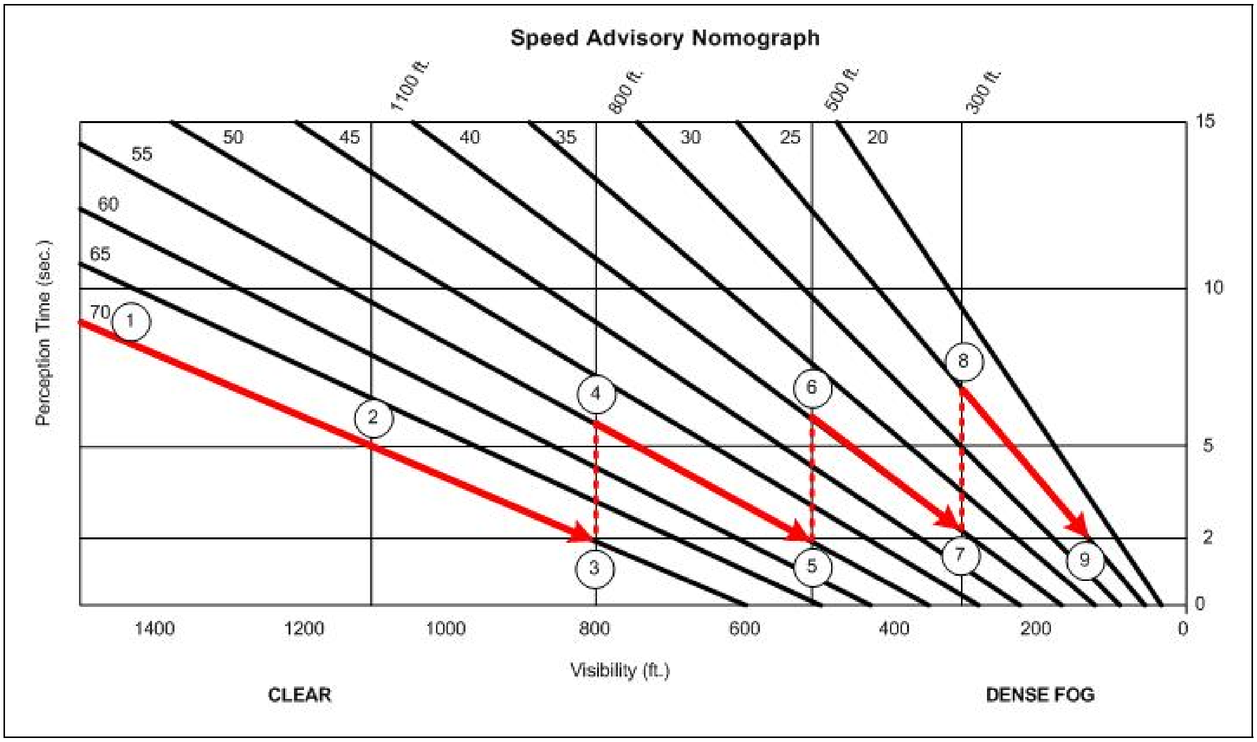


Figure 2. Speed Advisory Nomograph Used to Select Suggested Advisory Speeds in Georgia Automated Adverse Visibility Warning and Control System (*10*).

Response Criteria

Table 13 contains a summary of the triggers used in other states for implementing traffic management responses. In most states, traffic management responses consist of displaying speed advisory messages on DMSs. The table shows the types of messages that are displayed for the various visibility conditions.

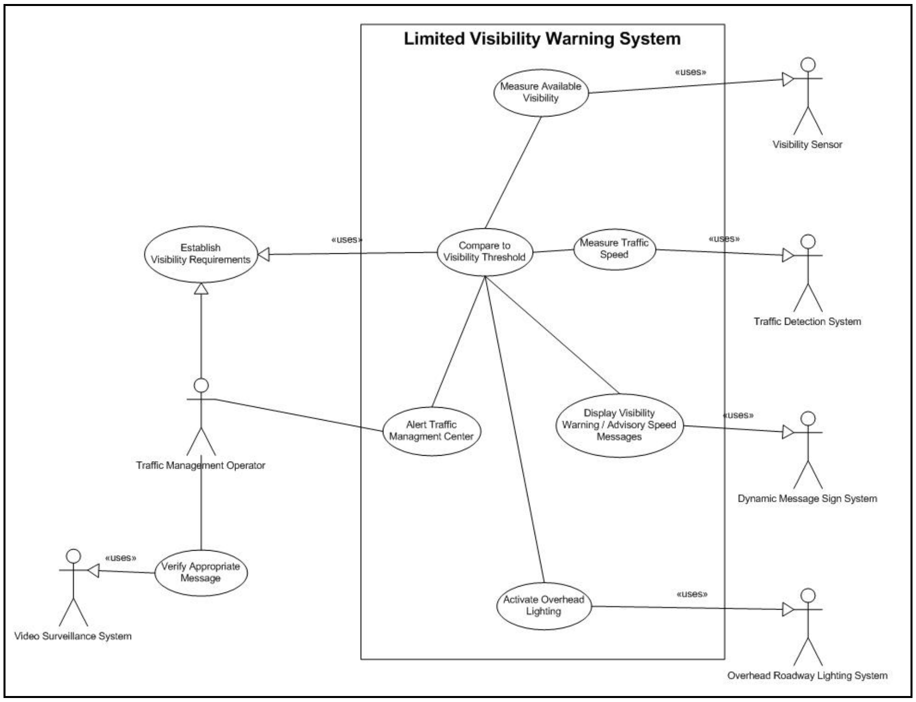


Figure 3. Logical Architecture for a Typical Limited Visibility Warning System.

Table 13. Summary of Visibility Criteria Used by Other States in Implementing Traffic Management Responses to Limited Visibility Conditions (*8*,*9*,*10*).

Location	Criteria	Traffic Management Action
Georgia	Visibility • > 1100 ft • 800 – 1100 ft • 500 – 800 ft • 300 – 500 ft • < 300 ft Speed	No Speed Advisory "CAUTION / FOG AHEAD" with "ADVISE 70 MPH" "CAUTION / FOG AHEAD" with "ADVISE 55 MPH" "CAUTION / FOG AHEAD" with "ADVISE 40 MPH" "CAUTION / FOG AHEAD" with "ADVISE 25 MPH" Measured Speed
Tennessee	Visibility • < 1320 ft • < 480 ft • < 240 ft Speed < 45 mph	Advisory Messages / Reduce speed to 50 mph Reduce speed to 35 mph Close Interstate "SLOW TRAFFIC AHEAD" message
Utah	Visibility • > 820 ft • 650 – 820 ft • 500 – 650 ft • 330 – 500 ft • 200 – 330 ft • < 200 ft	No Message "FOG AHEAD" "DENSE FOG" with "ADVISE 50 MPH" "DENSE FOG" with "ADVISE 40 MPH" "DENSE FOG" with "ADVISE 30 MPH" "DENSE FOG" with "ADVISE 20 MPH"

HIGH-WIND WARNING SYSTEMS

Most states have deployed wind warning systems. Generally, wind warning systems have been deployed in the following applications and situations:

- at bridges and overpasses where high-profile vehicles are susceptible to overturning winds,
- in mountain passes where wind speeds can change dramatically by elevation, and
- in rural sections of freeways where the topography tends to produce a natural wind tunnel.

Sample Deployments

The discussion below represents a summary of the types of high-wind warning systems that have been deployed in other states.

Oregon

The Oregon Department of Transportation (ODOT) has several high-wind warning systems (*11*). One system (the South Coast System) covers a 27-mile stretch of US 101 that runs through a mountain pass between Port Orford to Gold Beach. The system uses a local wind gauge (anemometer) to monitor wind speeds at the crest of the mountain pass. The wind gauge connects to a controller, which activates flashing beacons on static signs placed at both ends of the stretch of highway. The static signs contain the legend "CAUTION / HIGH WINDS / NEXT 27 MILES / WHEN FLASHING." ODOT uses a dial-up telephone connection to provide communications between the controller and the flashing beacon. The controller activates the beacons when the average sustained wind speed exceeds 35 mph for more than 2 minutes. The controller constantly monitors the wind speeds and deactivates the flashing beacons when the average wind speed drops below 25 mph for more than 2 minutes.

The system is also connected to Oregon's Highway Travel Conditions Reporting System (HTCRS). When the controller activates the flashing beacon, it also issues an alert to ODOT's Traffic Operations Center (TOC). Operators in ODOT's TOC verify that the system is functioning as designed and then post warnings on ODOT's TripCheck website that high-wind conditions have been detected in the pass.

ODOT has also installed a similar type of system on US Highway 101 on the Yaquina Bay Bridge. Like the South Coast System, an anemometer provides a controller with average wind speed measurements at the apex of the bridge. The controller activates flashing beacons on static signs when the average wind speed exceeds 35 mph for more than 2 minutes. The static signs advise travelers that high-wind conditions exist on the bridge. The controller deactivates the flashing beacons when sustained wind speeds drop below 25 mph.

ODOT also uses wind gusts to determine when to close the bridge to vehicular traffic. ODOT uses a criterion of wind gusts in excess of 80 mph as the threshold for determining when to close the bridge.

In the original design of the system, ODOT had planned to use small DMSs located at each end of the bridge, but because of funding reasons, replaced the DMSs with static signs. Because the signs are located far enough upstream of the bridge, drivers are provided sufficient warning to turn around on existing roads located under both ends of the bridge.

Also, like the South Coast System, the high-wind warning system provides wind advisory and bridge status information to ODOT's HTCRS. Operators in the TOC receive alerts when the wind speeds activate the system, and after verifying the conditions, the operator posts the status information on the TripCheck website. TOC operators also use pagers, email, and fax messages to notify other agencies and maintenance personnel that high-wind conditions exist on the bridge.

California

The California Department of Transportation (Caltrans) often installs high-wind warning systems in conjunction with other weather sensors at known trouble locations (*12*). An example of this type of installation can be found on I-5 and State Route 120 in the Stockton-Manteca area of San Joaquin County. This valley is prone not only to limited visibility conditions (blowing dust during the summer and dense, localized fog in the winter), but also frequently experiences high-wind conditions. The system consists of 36 vehicle detection sites and 9 environmental sensing stations deployed along freeways. Each vehicle detection site uses a pair of inductive loop detectors connected to a Caltrans Type 170 traffic signal controller to provide speed measurements of the traffic stream. Among other sensors, each environmental sensing station includes a rain gauge, a forward-scatter visibility sensor, and an anemometer (for measuring wind speed and direction). Each environmental sensing station is connected to the Stockton TMC. When the system detects average wind speeds in excess of 35 mph, it automatically posts "HIGH WIND WARNING" messages on corresponding DMSs that have also been installed throughout the region. Operators in the TMC have the capabilities to override automatic advisories that have been posted by the system.

Montana

As part of a comprehensive road weather management program, the Montana Department of Transportation (MDT) has installed a network of 59 environmental sensing stations throughout the state (*13*). These sensors provide MDT with real-time weather and pavement condition information at strategic locations throughout the state. While MDT deployed the system to assist in primarily winter maintenance and information dissemination activities, MDT is using the sensors in the Bozeman/Livingston area as part of a high-wind warning system on a 27-mile stretch of I-90 (*14*). In addition to the environmental sensing station, MDT has installed four DMSs in the corridor: two at each end of the section and two at the middle of the section. When the average wind speed exceeds 20 mph, the system automatically sends traffic and maintenance managers a notification to alert them to a developing situation and the managers post "CAUTION: WATCH FOR SEVERE CROSSWINDS" messages on the DMSs. When wind speeds exceed 39 mph, MDT requires high-profile vehicles to exit the freeway and seek alternative routes through the Livingston area. A typical restriction message reads "SEVERE CROSSWINDS: HIGH PROFILE UNITS EXIT."

Nevada

The Nevada Department of Transportation (Nevada DOT) operates a high-wind warning system on a 7-mile section of US 395 in the Washoe Valley, between Carson City and Reno (*15*). This section of highway frequently experiences crosswinds in excess of 70 mph. Nevada DOT uses the system to provide drivers with advance warning of high-wind conditions and to prohibit travel of designated high-profile vehicles when severe crosswinds exist.

The system uses an environmental sensing station to measure and transmit every 10 minutes wind speed and other weather information to a central control computer located in the Reno Traffic Operations Center. If high-wind conditions exist, operators in the Reno TOC use dynamic message signs located at each end of the valley to warn travelers and issue vehicle restrictions. Nevada DOT will recommend that high-profile vehicles not enter the area when average wind speed or wind gusts exceed 15 mph and 20 mph, respectively. Nevada DOT issues high-profile vehicle prohibitions for the area when average wind speeds exceed 30 mph or when wind gusts exceed 40 mph.

Operators also use a highway advisory radio system to broadcast prerecorded messages in the region.

System Architecture

Figure 4 shows a typical architecture for most high-wind warning systems. Most systems have been designed to be autonomous, with operators in the control center establishing a threshold for when field devices should be activated and receiving notification when the system has been activated. From a field component standpoint, most systems include some type of sensing station to monitor wind speeds and directions, a field process for making control decisions, and a system for notifying the public when high-wind conditions exist.

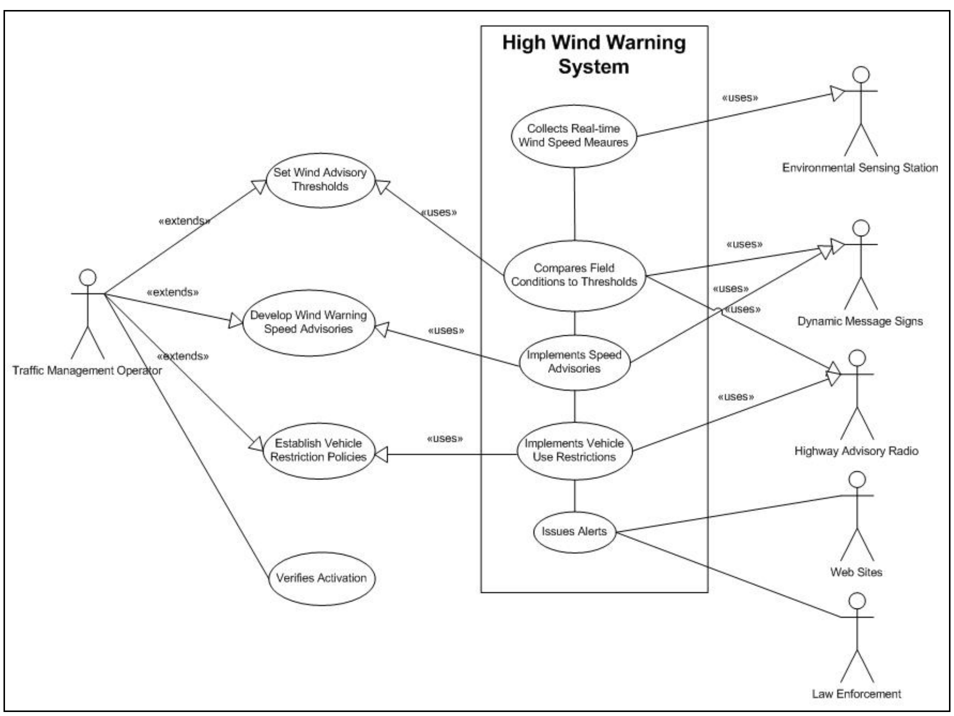


Figure 4. Logical Architecture for a Typical Automated High-Wind Warning System.

Response Criteria

Table 14 summarizes the criteria that various states are using to issue wind warning advisories and vehicle type prohibitions. Most states do not take action until average wind speed approaches 15 to 20 mph. Most states generally issue wind warning advisories for wind speeds of less than 40 mph. When wind speeds are in excess of 40 mph, most states consider restricting high-profile vehicles from using the facility.

Table 14. Criteria Used to Produce Wind Warning Advisory Messages (*12,14,15*).

State	Criteria	Threshold	Messages
Montana	Average Wind Speed	Avg. = 0 – 20 mph	No Message
		Avg. = 20 – 39 mph	"CAUTION: WATCH FOR SEVERE CROSSWINDS"
		Avg. > 39 mph	"SEVERE CROSSWINDS: HIGH PROFILE UNITS EXIT"
Nevada	Average Wind Speed/Gusts	Avg. / Gusts < 15 mph	No Message
		Avg. = 15 – 30 mph Gusts = 20 – 40 mph	High-Profile Vehicles "NOT ADVISED"
		Avg. > 30 mph Gusts > 40 mph	High-Profile Vehicles "PROHIBITED"
California	Average Wind Speed	Avg. > 35 mph	"HIGH WIND WARNING"

The TTI Houston Office developed a Wind Warning Calculator to assist local area transportation and law enforcement agencies in determining when to warn, restrict, or close area bridges due to high winds (see Figure 5) (*16*). This Wind Warning Calculator was developed using research from Carr and Rose (*17*), who examined the crosswind stability of vehicles on bridges in England. Carr and Rose conducted wind tunnel tests on different high-profile vehicles to determine the crosswind speed needed to produce a moment vector capable of overturning different types of trucks traveling at different speeds. Figure 6 shows the different types of vehicle classes for which the wind tunnel tests were performed, while Figure 7 shows the crosswind speed that produced a moment vector large enough to overturn the vehicle. Using a worst-case scenario (i.e., a Luton van with a 30 percent reduction in wind speeds), the TTI researchers developed a system that computed the normal crosswind vector and compared it to the overturning wind speed needed to provide truck speed advisories.

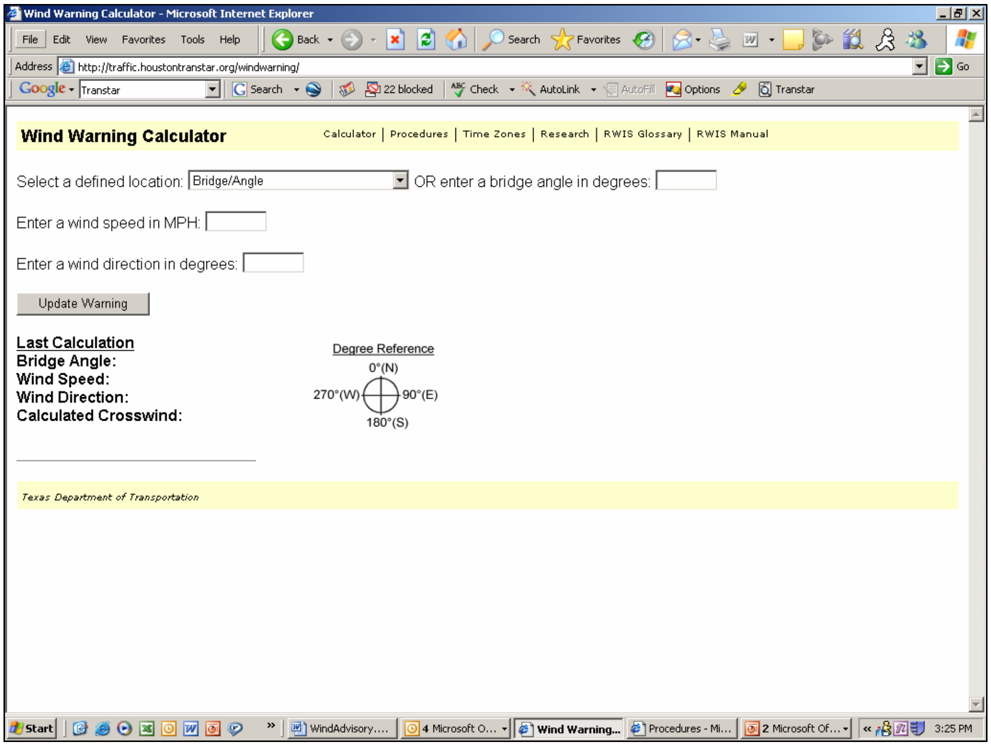


Figure 5. Wind Warning Calculator Developed for Houston Transtar (*16*).

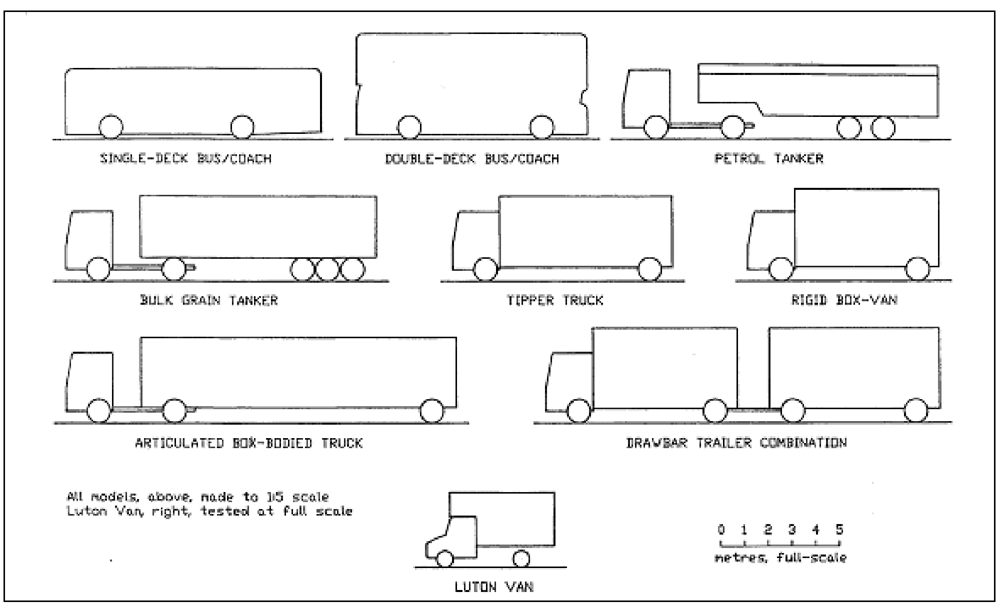


Figure 6. Types of Vehicles Studied in Wind Tunnel Tests (*17*).

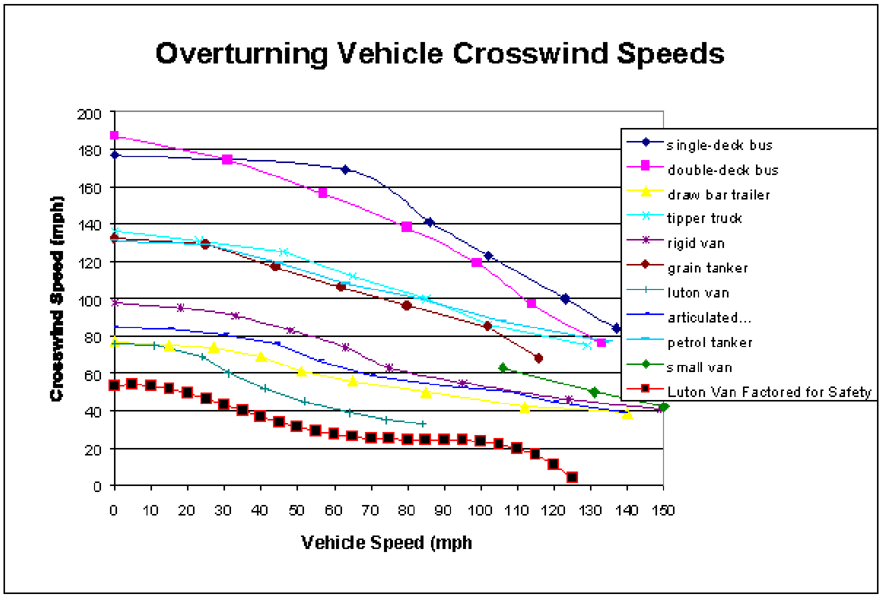
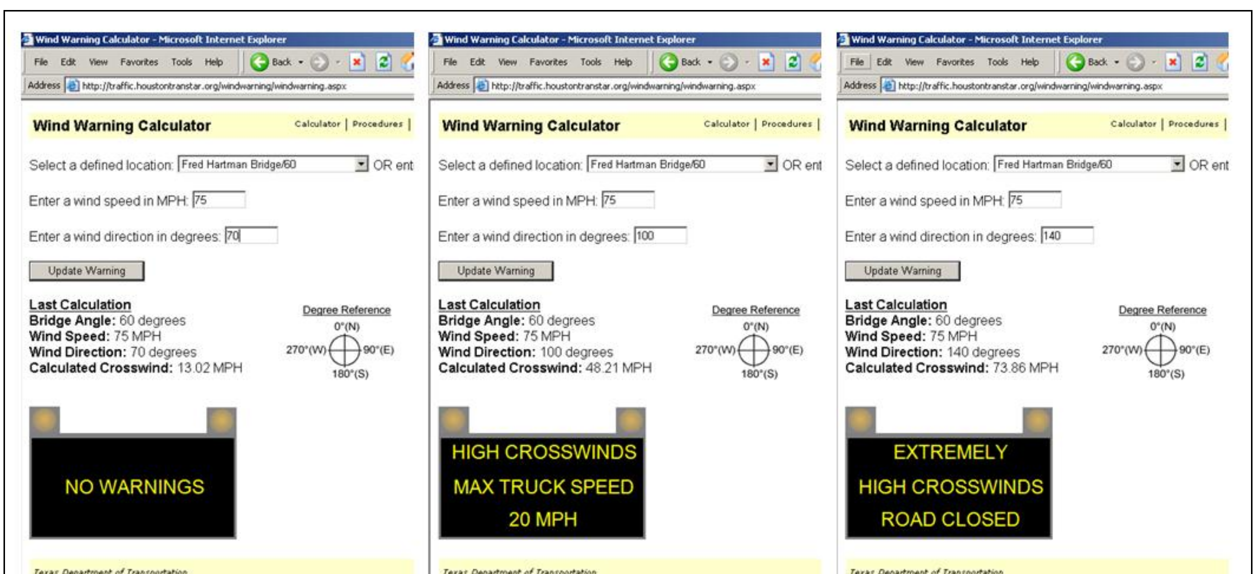


Figure 7. Calculated Crosswind Speeds versus Overturning Vehicle Speeds (*17*).

To use the calculator, the operator enters the location of interest (or the bridge angle in degrees), and the wind speed and direction at the given location. The system then calculates the crosswind component and displays the resulting truck speed advisory. Recommended truck speed advisories can range from 55 mph to 20 mph. The system generates a road closure advisory when the calculated crosswind vector exceeds 70 mph. Figure 8 shows an example application of the type of advisory produced by the Wind Warning Calculator.



a) No Advisory Needed b) Truck Speed Advisory c) Road Closure Advisory

Figure 8. Example Application of Wind Warning Calculator (*16*).

FLASH FLOOD/URBAN FLOODING

According to the National Weather Service (*18*), three types of flooding events exist:

- **Flash Floods:** Flash floods are short-fuse weather events, typically lasting 6 hours or less and usually occurring within a few minutes or hours following an excessive rainfall event. They can also be caused by a man-made event, such as a dam or levee failure. Flash floods cause most of the fatalities associated with flooding events. Usually, less warning lead time is provided for flash flooding, which requires quick action on the part of the public.
- **Urban Floods:** Flash flooding is most severe in urban areas. Urbanization increases runoff by two to six times over what would occur in natural terrain. Flood waters can fill streets, freeway underpasses, and parking lots and can sweep away cars.
- **River Floods:** Heavy rainfall covering a widespread area (such as a large portion of a watershed) over a prolonged period of time (like several days) can cause river flooding. Typically, river flooding begins as a high crest on the upper part of a watershed that takes several days to move downstream. Due to the slow nature of river flooding, ample advance warning is provided to evacuate people or property in the path of the flooding.

Flash flooding is a relatively common event in Southeast Texas but is usually most severe near major watersheds like the Colorado, Brazos, San Jacinto, and Trinity Rivers and near urban metropolitan areas like Houston. Tropical systems during the summer and early fall, and strong winter storm systems can cause widespread flooding and flash flooding across an area. Flash flooding can also be produced by strong slow-moving thunderstorms especially during the spring and summer months.

Sample Deployments

City of Dallas Flooded Roadway Warning System

In April 2000, the City of Dallas activated its Flooded Roadway Warning System (*19*). As of 2006, the system has been deployed at 44 intersections within the Dallas city limits.

The system is comprised of three components:

- a central computer system,
- one sensor at each site, and
- one to six changeable signs at each site.

The sensor monitors the elevation of a nearby stream and reports every 20 minutes to the central computer.

When the flood water reaches the edge of the roadway, a float switch tells the sensor to signal the sign to change to the warning text and turn on the flashing lights. The sign sends a message back to the sensor confirming that everything is working properly. The sensor radios all this information back to the central computer. Pages are sent to staff and messages are printed out at the appropriate Street Services district alerting them of the need to place barricades at this location as soon as possible.

The signs and sensors are battery powered and recharged with solar cells. All communication between the sensors and signs and sensors and the central computer are by radio.

The sensors normally control the signs without intervention from the central computer; however, the central computer can issue commands to turn on the signs and lights.

The signs include changeable text messages and red flashing lights. In the non-alarm state, the lights are off and the sign shows "High Water When Flashing." In alarm state, the lights alternate flashing and the sign changes to "Do Not Enter High Water." The signs and lights are equipped with sensors to detect the status.

SNOW/ICE DETECTION SYSTEMS

Apart from reducing friction between the road surface and vehicle tires, snow can also reduce visibility levels significantly. This, in turn, reduces vehicle operating speeds and levels of service of freeway systems. In addition, the risk of vehicle crashes increases during and immediately after snow events; FHWA data for 2001 show that nearly 20 percent of weather-related vehicle crashes occurred on snowy or slushy pavements. FHWA also reports that approximately 74 percent (or nearly 3 million miles) of the roads in the United States lie in regions that are likely to receive more than 5 inches of snow every year. Figure 9 shows a map of the part of the United States that is likely to experience more than 5 inches of snow annually. North Texas is included in the area.

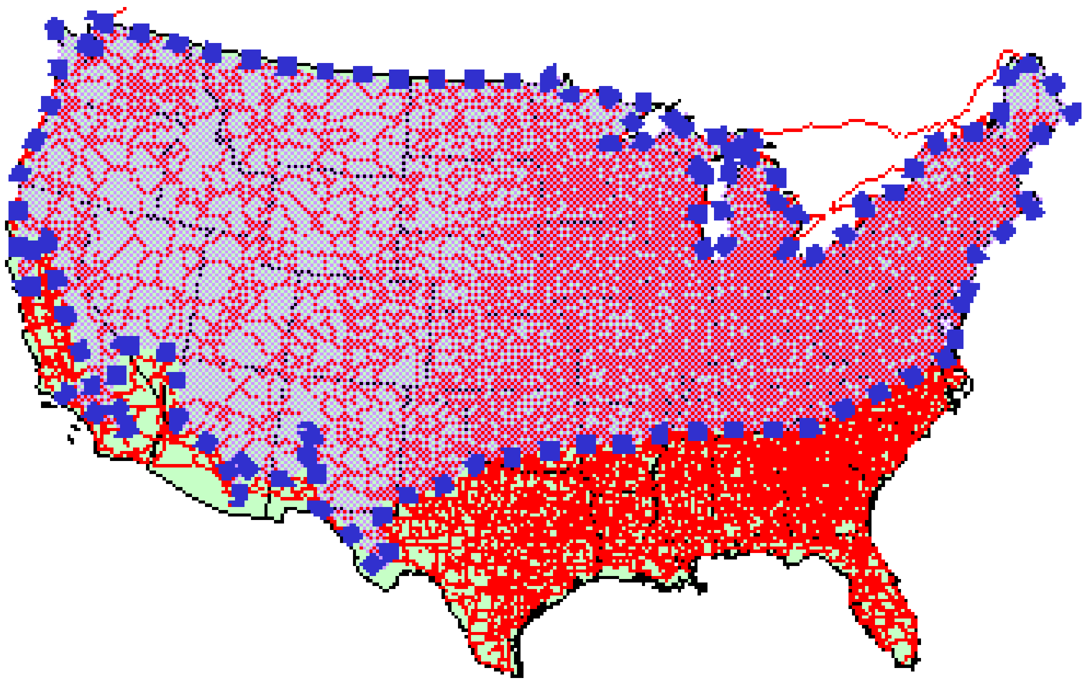


Figure 9. Map of USA Showing Areas Likely to Experience Snow/Ice Events (*20*).

State of Practice in Snow Related Traffic Management

Management and maintenance of freeways before, during, and after snow events has been a lasting concern for DOTs as well as local transportation agencies. Prior to the development of automobiles, there was limited traveling on snow or ice. However, after automobiles were introduced, people started looking for ways to move around irrespective of the weather conditions. Use of deicing salts (primarily sodium chloride) for removing the ice accumulated on roadways has been prevalent since 1941 (*21*). Negative impacts of heavy salt use on roadside environments, water supplies, and vehicles gradually led researchers and practitioners to look for advanced technologies as well as more efficient operational strategies. According to a survey conducted by the Transportation Research Board Committee on Weather Research for Surface Transportation, most state DOTs have adopted, to various extents, operational strategies for maintaining freeway infrastructures during and after snow events. The survey also indicated a need to develop new strategies to deal with this problem. The document Weather Responsive

Traffic Management Concept of Operations by FHWA (*22*) recommends a three-step procedure to address the issue:

- proactive planning for the event based on weather forecasts and impact assessments,
- activities undertaken in response to system conditions during the event, and
- activities undertaken after the event to help restore the system to normal.

System Architecture

Figure 10 represents a flow chart showing the typical flow of operation (system architecture) for a weather related traffic management system (*23*).

Ice and Snow Detection/Surveillance Systems

An ice detection system consists of two primary parts. The first part consists of pavement or weather sensors located at road sites. The second part is composed of a computer or data processing unit that processes the information gathered by the sensors and presents it to the user. Surface sensors can measure pavement surface conditions as well as subsurface conditions. There are primarily two types of surface sensors: active sensors and passive sensors (*24*). Active sensors generate and emit a signal and analyze the radiation reflected by the targeted surface to determine the surface conditions, whereas passive sensors detect the radiation emitted by an external source.

Ice detection systems currently used in the United States are manufactured by five primary companies. The names of these companies and their products are listed in Table 15 followed by detailed descriptions about the sensors (*25*).

Table 15. Ice Detection System Manufacturers and Their Products.

Company Name (Origin)	Sensor Name
Surface Systems Inc. (SSI) (U.S.-based)	SCAN
Climatronics (U.S.-based)	FRENSOR
Vaisala (U.K.-based)	System Name: ICECAST, DRS50, ROSA
Aanderra Instruments (Norway-based)	Road Weather Station 4030
Boschung Mechatronics (Germany-based)	GFS 2000. It can be integrated with TMS 2000 which automatically sprays deicing chemicals on the roadway.

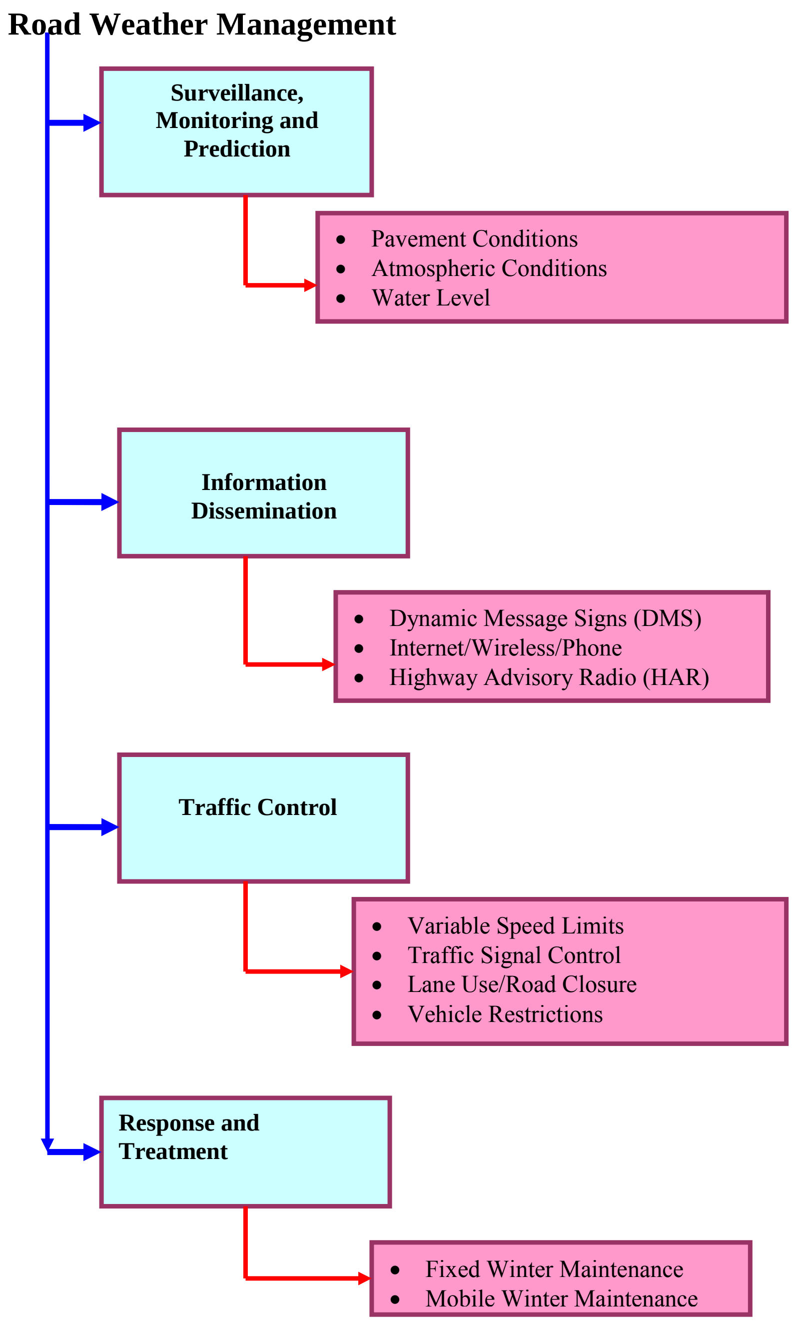


Figure 10. Control Flow in Weather Related Traffic Management (modified from *23*).

- SCAN is an in-pavement detector made by Surface Systems Inc. (SSI), which is the largest manufacturer of ice detection systems in the U.S. The functionalities of the SCAN sensor involve measuring temperature, determining the degree of wetness of the road surface (using capacitive techniques), and measuring conductivity to determine salinity (which is an indicator of the freezing point), and the amount of chemicals already on the roadway. These data are then processed by a computer or data processing unit located on-site or at a remote location, to inform the user about the roadway freezing conditions.

- The FRENSOR, manufactured by Climatronics, can actively change the temperature of the moisture on its surface and provide an output of the pavement temperature with a tolerance of about 0.5º C.
- The ICECAST ice warning system is manufactured by the company Vaisala, based in the U.K. The DRS50 measures electrical conductivity and polarization to identify the surface state of pavements and also calculates the freezing point of the roadway. ROSA (Road Surface Analyzer) measures the depth of water on a wet road as well as the wind speed and determines if there is a reduction in roadway friction coefficient.
- Aanderra Instruments, based in Norway, produces the Road Weather Station 4030. These pavement sensors can measure road surface temperature, surface wetness, freezing point, and presence of snow.
- GFS 2000 is produced by Boschung Mechatronics (based in Germany). It identifies threats of ice formation through actual measurements as well as a simulation of dangerous conditions. This system can be used with the TMS 2000, which automatically sprays deicing chemicals on the roadway.

FHWA conducted extensive tests and evaluations on ice detection systems in 1993 and concluded that they were no longer experimental and did not need more evaluation at the federal level.

Closed-circuit television (CCTV) cameras are also used to monitor ice and snow conditions. Visibility can be measured by pointing the CCTV cameras at fixed objects at known distances, such as road signs. Visible Image Road Surface Sensors can be used to judge the road surface conditions by applying image processing techniques on video images captured by CCTV cameras. The characteristics of the video images from CCTV cameras are matched to a set of characteristics stored in the database corresponding to each type of surface condition (*24*). Figure 11 provides an illustration of this concept.

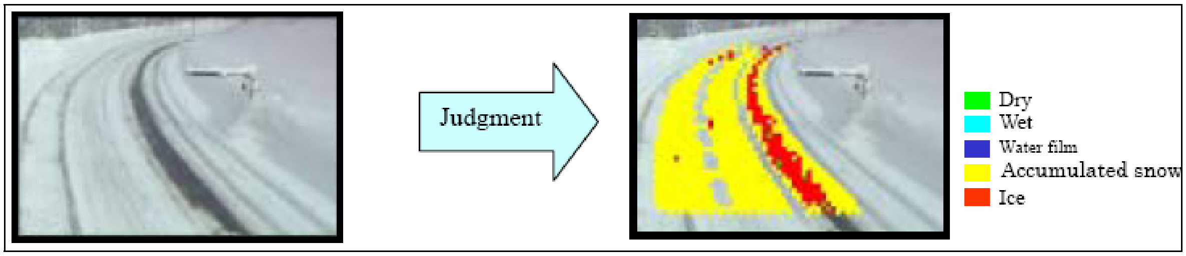


Figure 11. Processing of CCTV Images to Characterize Surface Conditions (*24*).

Practices and Technologies for Snow Removal

Deicing and Anti-icing Approach

The most common deicing approach is the application of salt on the snow or ice formed on roads, but extensive use of salt as a deicing agent has the following disadvantages (*26*):

- Salt is an extremely corrosive material and may corrode the vehicles and the roadways significantly.
- Salt in bulk quantities is toxic to the environment. The salt applied on existing snow is often shoved away to the side by vehicles and goes into drains. This may contaminate the soil and/or ground water.
- Mass application of salt may also be expensive. Because the salt applied on ice forms a slush that is plowed away to the side of the road, repeated applications of salt are necessary for complete removal of the snow.
- Because spraying of salts is normally started after the snow event has started, the salt has to melt through a layer of ice in order to reach the pavement surface. A few heavy storm events may be exempt from the penetration of salt (because of high rate of precipitation) and in such cases the application of salt becomes ineffective.

The large amount of money spent every year on deicing operations as well as the disadvantages of salt application have led transportation agencies to pay more attention to anti-icing operations that prevent the snow from sticking to the pavement surface in the first place. Anti-icing is a proactive approach that involves application of anti-icing chemicals (mostly liquids) on the roads before the advent of the snow event. Such an anti-icing system mainly relies on some kind of weather information system (e.g., RWIS) to gather information about upcoming snow events. After the event has been detected, the anti-icing chemicals can be sprayed on the roadways either manually or by automated systems already installed on the pavements. The most commonly used anti-icing chemicals are liquid calcium chloride, liquid magnesium chloride, liquid sodium chloride (salt brine), liquid potassium acetate, and calcium magnesium acetate (CMA).

An automatic anti-icing system consists of sensors embedded in pavements and sprayers located on the roadways. Such a system can often be integrated with the road weather information system. The sensors on the RWIS detect the freezing point of moisture on the pavement surface and trigger the sprayers that spray the anti-icing chemical all over the targeted area. Depending on the period and duration of the snow event, the application of chemicals may need to be carried out multiple times.

In early 1991, the Strategic Highway Research Program (SHRP) of the National Research Council funded a multiyear study entitled, "Development of Anti-icing Technologies" under project H-385 (*26*). The goals of this study were to examine conditions under which anti-icing may be more effective and to come up with effective strategies for implementation. The project analyzed the relative costs of deicing and anti-icing strategies, considering factors such as accidents, time delays, material and equipment costs, and labor costs. During the study, researchers compared the performance of the conventional ice and snow control policies of each of nine participating states with the performance of new anti-icing techniques. RWIS atmospheric and pavement sensors were incorporated in the test sites (except one in Maryland), which helped in making informed decisions about the timing and application of anti-icing chemicals. Anti-icing techniques were used at the test road sections, whereas deicing techniques were used on correspondingly similar control sections. The findings of this research study indicated the following:

- Less chemical was used for anti-icing operations than for deicing operations.
- The use of liquid chemicals and prewetted salt for anti-icing operations was successfully demonstrated during several storm events.
- Application of anti-icing chemicals was effective if applied at the appropriate time and not under severe storm conditions of extremely cold pavement temperatures and high winds.

- Accurate weather forecasting for the highway systems environment was necessary for the success of the anti-icing program.
- Training of maintenance personnel in anti-icing operations is necessary for the success of the program.
- The benefits from the anti-icing program were significantly enhanced by the willingness of the maintenance personnel to work in cooperation with each other and also to learn from each others' experiences.

Table 16 lists the benefits of RWIS and anti-icing programs in terms of mobility, safety, and productivity of transportation systems.

Table 16. Performance Measures of RWIS and Anti-Icing Programs (modified from *27*).

Performance Measures	Road Weather Information System (RWIS) Benefits	Anti-icing Benefits
Mobility	• Reduced travel times • Improved traveler information • Reduced accident frequency • Less disruption of emergency vehicles	• Reduced number of road closures • Improved traveler information • Reduced accident frequency • Decrease in insurance claims
Safety/Productivity	• More efficient response strategies (right resources, in right place, at right time) • Reduced maintenance costs (staff, equipment, and materials) • Assist with crew scheduling • Facilitate data sharing	• Less snow/ice bonding, facilitating more efficient plowing • Reduced maintenance costs (overtime pay and material) • Reduced time to clear snow/ice from roads • Less abrasive cleanup

Although the benefits of anti-icing programs are widely accepted, such programs may have some disadvantages too. Some of these disadvantages can be avoided with proper use of information provided by RWIS. Liquid anti-icing chemical usage in windy conditions can cause blowing snow to adhere to pavements. Pretreating roads with liquid chemicals may cause slippery conditions or lead to surface freezing if pavement temperatures fall below specific thresholds. Pretreated areas may necessitate subsequent treatment with solid materials. Level of service (and customer satisfaction) disparities may exist where different agencies or maintenance units are responsible for adjacent road sections. If one unit employs anti-icing techniques and the other does not, motorists may travel from a road section with bare pavement directly onto a snow-covered section.

Snow Plow Operations

Snow plow operations constitute an important aspect of weather related traffic management. They are used to remove the snow accumulated on the road surface and shoulders, spread anti-icing/deicing material on the road, or even to spread sand that improves the traction between the vehicle and the road. To effectively address all the areas and streets affected by the snow, the transportation agencies need to ensure proper routing and scheduling of the snow plow. In the past, snow plow routing was done manually and the practice was to get the highways back to normal driving conditions at a fixed cycle-time. This fixed cycle-time is the time taken by the snow plows to get the highways back to normal condition by following a fixed routing schedule. This kind of an arrangement created the problem of "deadheading," which is defined as the time when the truck moves with the plow blade not in service, e.g., driving from the truck station to the start of a route, or driving between service areas.

Researchers gradually realized the importance of routing the snow plows effectively to ensure operational efficiency. McHenry County in Illinois implemented a Geographic Information System (GIS) website to enhance operational efficiency by optimum routing of snow plows and salt applications. This website shows the current locations of the snow plows on a map and enables the transportation managers to optimize their routing so that more areas can be covered in less time. This saves the snow plows from having to make 'dead trips' to the management office after the completion of work at every site. Columbia County in Wisconsin has implemented a system that can also monitor and regulate the amount of materials and liquids spread onto roadways by snow and ice plowing vehicles. This gives the traffic manager more control over the quantity of deicing/anti-icing material to be applied and also the exact locations where the material should be applied. The dispatcher can watch the condition at the site from the office and also can communicate with the plow driver if necessary.

In addition to this, GIS and global positioning systems (GPS) have been used to ensure safe operation of snow plow vehicles. It had been observed over the years that the operation of snow plow vehicles on roads completely covered with snow presented the plow drivers with a dangerous situation. It becomes difficult for the plow operator to stay on the road, which becomes particularly dangerous in mountain terrains. Snow plows deviating from the lanes and hitting guardrails, or traffic coming from the other direction, was a common occurrence until the late 1990s. In 1999, CalTrans recorded 194 accidents for vehicles involved in snow operations. These risks are now addressed by Advanced Vehicle Control System technologies which have been incorporated into the U.S. Department of Transportation's (USDOT) Intelligent Vehicle Initiative (IVI) program. The snow plows are now being equipped with lateral lane indication and forward collision warning systems. Additionally, snow plows are being enhanced by relying on the use of differential global positioning system (DGPS) and a geo-spatial database to locate fixed objects such as lane boundaries, guardrails, and sign posts. Figure 12 shows a schematic of information transfer between the base station and winter maintenance fleet.

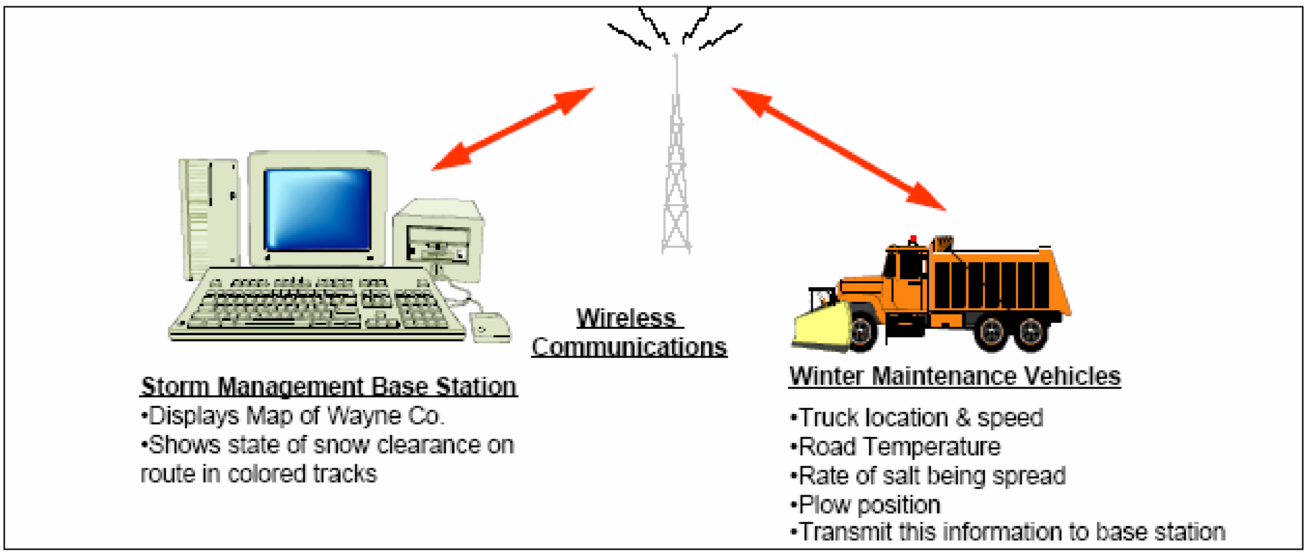


Figure 12. Functional Schematic of ITS Concept for Winter Fleet Management (*28*).

Ice/Snow Related Traffic Management at TMC

Pavement and environment temperature and humidity conditions are used in the traffic management center to predict the weather condition that can be expected in the near future. However, depending on the time scale of prediction and also the weather scale of prediction, different actions are taken by the transportation agencies. Table 17 lists predictions corresponding to different weather scales as well as the decisions that transportation officials need to make in response to each prediction.

Table 17. Weather and Transportation Decision Scales (modified from *29*).

Weather Scales	Time Scale	Decision Scales	Transportation Decisions
Climatic	Months to Years	Long-Term Planning	• Deploying infrastructure/systems • Procuring equipment or materials • Coordinating evacuation planning with adjacent states
Synoptic/Meso	Hours to Days	Short-Term Actions	• Mobilizing and treating snow/ice • Mobilizing and dispersing fog • Modifying speed limits • Closing threatened roads/bridges
Micro	Seconds to Hours	Immediate Warnings	• Advising reduced visibility • Notifying drivers about high water

As shown in Table 17, the scales of prediction based on time as well as weather can demand different actions from the transportation agencies. Whereas weather predictions in the climatic scale may require the authorities to plan a long-term action, micro-scale weather warnings require immediate action in terms of roadway advisories and warnings.

TMCs make decisions regarding what actions to take based on the severity of the weather event(s). The justification is made by the control factors that were predefined by local agencies. Table 18 shows the speed control strategies adopted by the Washington State Department of Transportation (WsDOT) during weather events. The control factor is the visibility distance corresponding to different weather conditions. As illustrated by the table, whereas a visibility distance of more than ½ mile may not require any significant reduction in the speed limit and does not impose any tire regulations, a visibility distance of less than 0.1 mile causes a significant reduction in the speed limit (reduced to 35 mph) and imposes the requirement for tire chains. A similar guideline can be developed for ice/snow related events based on friction values between vehicle tires and the road as well as the thickness and state of snow on the pavement.

Table 18. WsDOT Speed Management Control Strategies during Snow/Ice Events (*30*).

Weather Conditions	Pavement Conditions	Control Strategies
• Light to moderate rain • Visibility distance greater than ½ mi (0.8 km)	• Dry • Wet	• Speed limit at 65 mph (104.5 kph) • No tire regulations
• Heavy rain • Fog • Visibility distance less than 0.2 mi (0.32 km)	• Slushy • Icy	• Speed limit reduced to 55 mph (88.4 kph) • Traction tires advised
• Heavy rain or snow • Blowing snow • Visibility distance less than 0.1 mi (0.16 km)	• Shallow standing water • Compacted snow/ice • Deep slush	• Speed limit reduced to 45 mph (72.4 kph) • Traction tires required
• Freezing rain • Heavy rain or snow • Blowing snow • Visibility distance less than 0.1 mi (0.16 km)	• Deep standing water • Deep snow/slush	• Speed limit reduced to 35 mph (56.3 kph) • Tire chains required

The advisories and warnings are passed to the driving public through DMSs, Internet, wireless phones, or highway advisory radios. These advisories and warnings enable drivers to prepare for the road condition lying ahead. This also enables people who are yet to start the trip, to choose another route or postpone the trip depending on the severity of the weather event and also on the importance of the trip to be made. Figure 13 shows a dynamic message sign on one of the roads in Washington State. This helps the drivers to reduce their speeds and safely negotiate the section of roadway covered by snow.

Figure 13. Washington State DOT Reduced Speed Limit on DMS (*31*).

Another mode of informing and warning the public about upcoming weather events is by the use of the Internet. Several DOTs are developing websites that display maps of the roadways and also show current weather conditions over different stretches of the roadways. Figure 14 shows a screenshot from the traffic and weather website developed by WsDOT. The user can zoom into particular freeways in such maps and can see the current weather conditions prevalent over those sections.

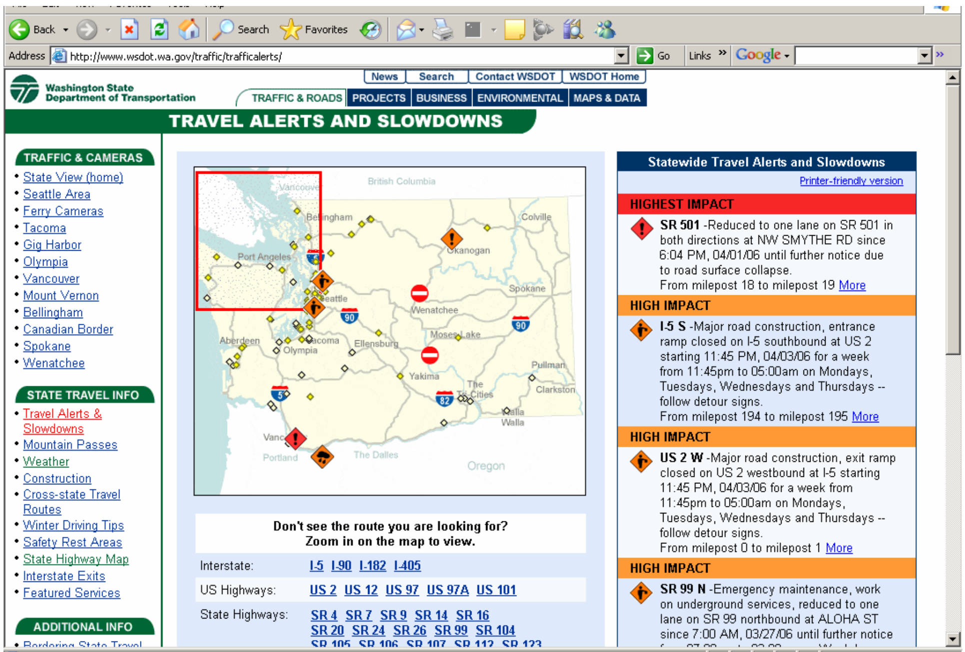


Figure 14. Screenshot from WsDOT's Traffic and Weather Website (*32*).

A similar system has been developed and implemented by the Nevada Department of Transportation (*33*). This system, apart from giving the condition of the freeway, also states the tire requirements imposed for the respective sections. A national map of this kind is generated by the National Oceanic and Atmospheric Administration (NOAA) on a daily basis. Such a map is given in Figure 15.

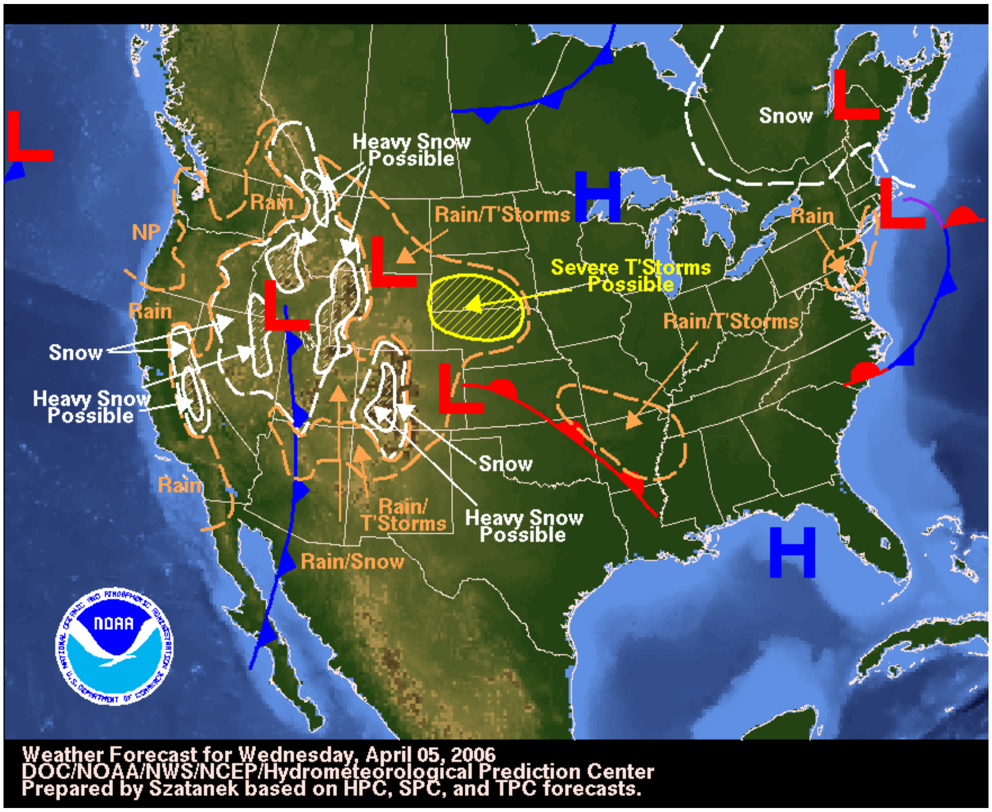


Figure 15. National Weather Forecasting by National Oceanic and Atmospheric Administration (*34*).

Federal Level Programs for Weather Related Traffic Management

Several nationwide programs are being conducted to study the research needs for weather related traffic management. The suggestions and recommendations of these studies are first implemented in the DOTs on a trial basis and are then implemented into regular practice depending on the outcomes of the trials. One such important study on the federal level is the Maintenance Decision Support System (MDSS) project.

The MDSS Project

The Maintenance Decision Support System project is a research and development project that is funded and administered by the FHWA Road Weather Management Program. The objective of this project is to produce a prototype tool for decision support to winter road maintenance managers.

The following five national laboratories have been participating in the development and implementation of MDSS:

- Army Cold Regions Research and Engineering Laboratory (CRREL),
- National Center for Atmospheric Research (NCAR),
- Massachusetts Institute of Technology–Lincoln Laboratory (MIT/LL),
- National Oceanic and Atmospheric Association Forecast Systems Laboratory (NOAA/FSL), and
- NOAA National Severe Storms Laboratory.

The MDSS project integrates the state of the art weather forecasting and data acquisition techniques with the road maintenance decision framework. Figure 16 represents a flow chart describing the flow of data in the MDSS functional prototype.

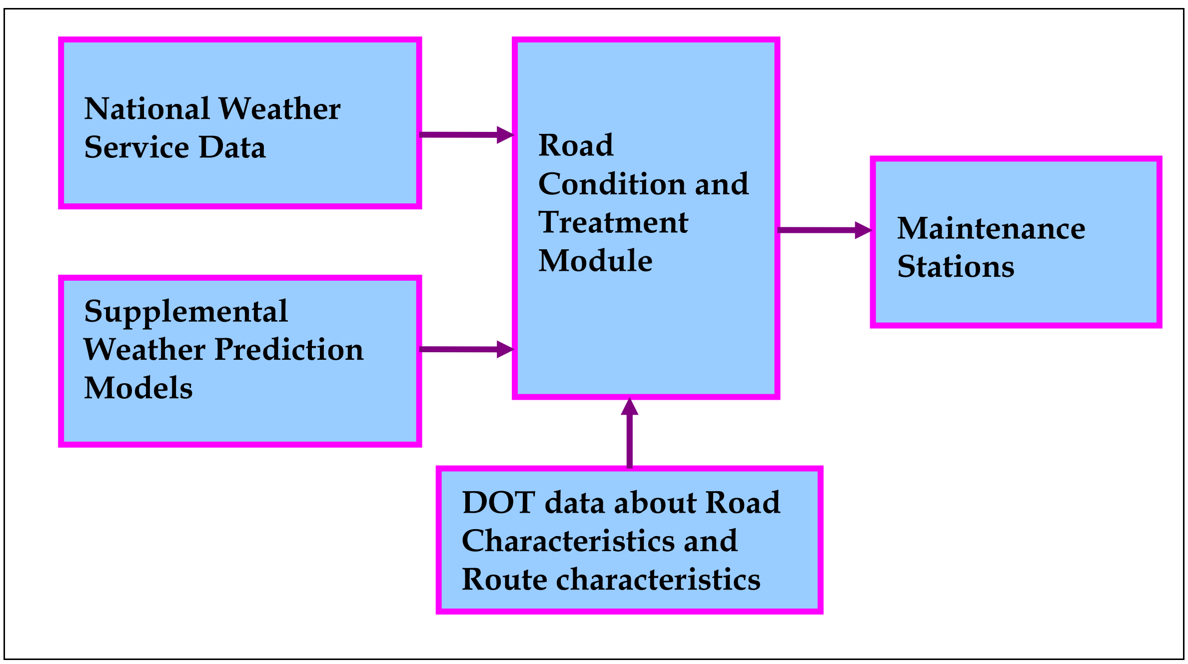


Figure 16. Flow of Data in MDSS Functional Prototype.

Figure 17 shows the main screen display of the MDSS module. It gives a weather alert summary over 48 hours. The individual dots on the map denote stations of observation or forecast. The user can zoom the map to any of the dots to give a more detailed picture. Weather data for points not directly measured or forecasted can be interpolated from adjacent stations.

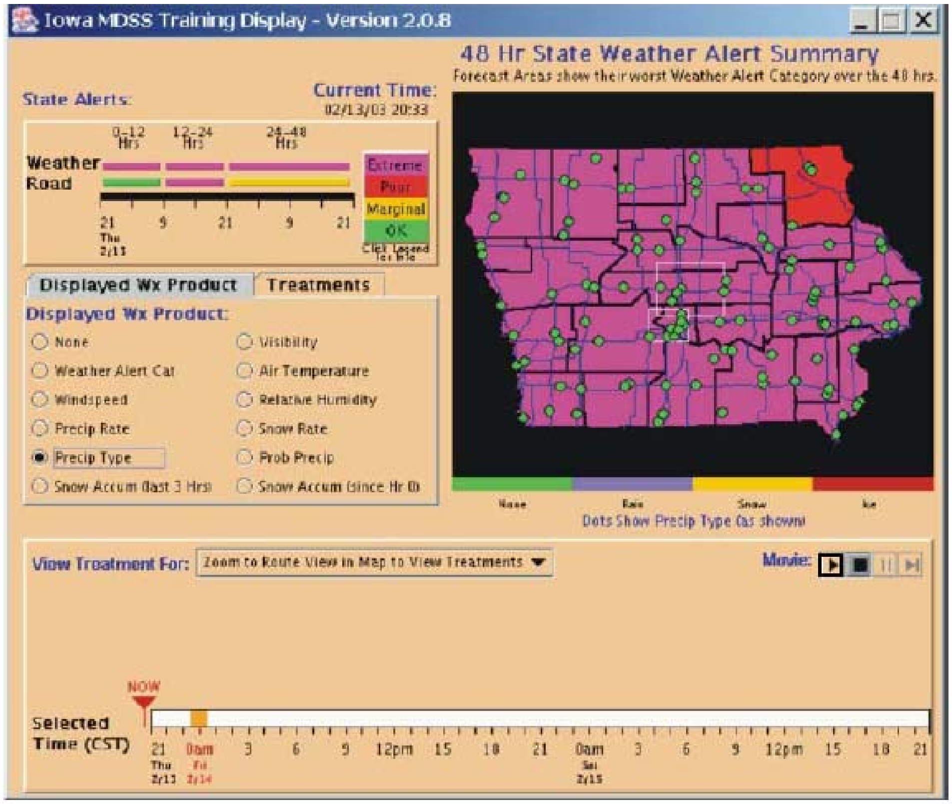


Figure 17. MDSS Weather Display (*35*).

Summary

We conducted a comprehensive review of pertinent technical literature to get an idea about the state of practice in snow and ice related traffic operations. Several research studies have proved the adverse effects of snow and ice on the functionality of transportation systems. DOTs in the states that receive a significant amount of snowfall every year have special programs and strategies designed to address traffic management during these events. As the northern part of Texas is likely to receive more than 5 inches of snow every year, it is imperative for TxDOT to have strategies and technologies that will enable them to maintain the transportation infrastructure during severe winter events.

ASSESSMENT OF WEATHER MONITORING TECHNOLOGIES

OVERVIEW

The objective of this task was to assess the weather monitoring technologies that are currently available and being deployed in freeway management applications. We limited the scope of our assessment to sensor technologies for weather events that are common in Texas. In this study, we primarily focus on four types of weather events – rain, flooding, wind, and low visibility. A detailed assessment of the different weather monitoring technologies is provided in Appendix B.

Currently, a variety of weather and road condition information is available from multiple sources across the country, including:

- Road Weather Information System – RWIS is a combination of technologies that collects, transmits, models, and disseminates weather and road condition information. The element of an RWIS that collects weather data is called the environmental sensor station (ESS).
- Meteorological Assimilation Data Ingest System (MADIS) – MADIS is a framework for a national clearinghouse of RWIS data. Some state DOTs provide the information to be entered into the database, which can then be distributed to users of road weather information.
- Maintenance Decision Support System – The MDSS project takes road weather data and information and merges them into a computerized winter road maintenance program that can help guide maintenance personnel in making better road treatment decisions.

SENSORS

The predecessors to road weather information systems were initially installed at airports. Their information was used to assist airport authorities in their operation of air traffic control. Similar systems were sold to highway and other agencies. Remote processing units (RPUs) with atmospheric and pavement sensors were installed along highways, and central processing units (CPUs) were installed in highway maintenance facilities (*36*).

Road weather information systems are made up of pavement sensors and other components similar to those in the National Weather Service (NWS). An RWIS may contain the following:

- atmospheric sensors that measure atmospheric temperature, relative humidity or dew point, wind speed and direction, visibility, and precipitation;
- pavement sensors that measure surface temperature, subgrade temperature, surface condition (wet, dry, or ice), the concentration of deicing chemical on the pavement, or the freezing point of the pavement;
- hydrologic sensors that measure water level, tide level, and tidal flow velocity;
- temperature profiles of roadways based on road thermal analysis;
- site-specific forecasts of weather and pavement conditions tailored to a highway agency's needs; and
- communications, data processing, and display capabilities for data dissemination and presentation.

The goal of this task is to determine the utility of existing technologies. It is not the intent of this research to conduct a comprehensive evaluation of each vendor product. The outcome of this task should help decision-makers decide what tools and technologies are applicable for different weather events and how they can be deployed to help improve freeway productivity as well as safety during weather events.

An environmental sensor station is a fixed roadway location with one or more sensors measuring atmospheric, surface, and/or hydrologic conditions. A typical ESS installation includes a thermometer to measure air temperature, a hygrometer for water vapor (dew point or relative humidity), an anemometer and wind vane, and a pavement sensor to monitor temperature, freeze point, and chemical concentration. A rain gauge and infrared sensor can measure precipitation occurrence, type, and intensity. By using sensors and video cameras mounted on a tower or next to it, operations and maintenance personnel can determine appropriate strategies and evaluate the outcome of those strategies.

Figure 18 shows a typical ESS tower and sensor configuration, including a wind sensor and camera mounted near or at the top of the tower, precipitation and radiation sensors several feet above ground level, and a snow depth sensor just above the roadway surface. A recent

FHWA document by Manfredi et al. (*37*) provides recommendations for placement of the sensors shown in this diagram.

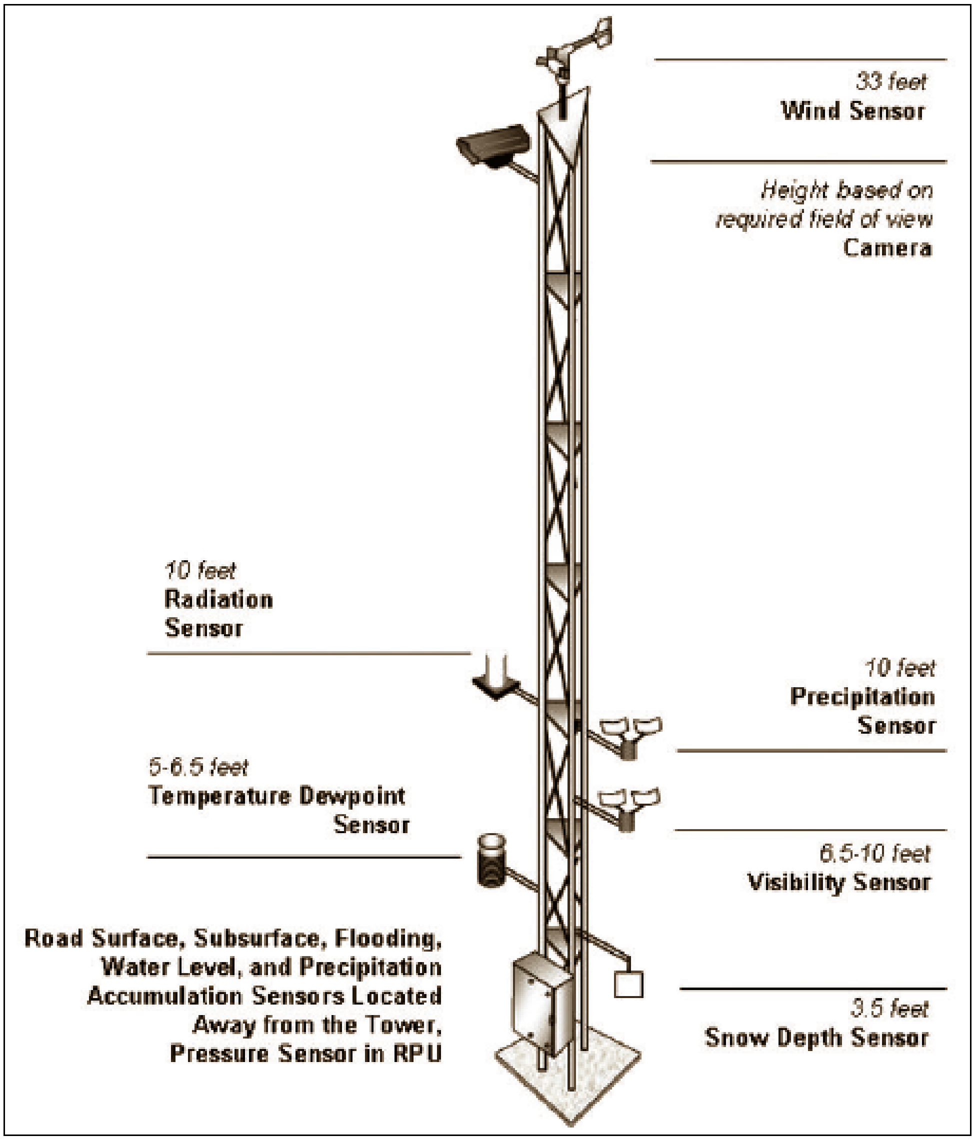


Figure 18. Typical Location of Tower-Based Sensors (*37*).

Table 19 provides a list of the most common ESS sensors. The sensors chosen for a particular site should reflect: (a) the results of the requirements analysis, i.e., how the observations will be used, and (b) the minimum road weather information required at that specific location (*37*).

Table 19. ESS Sensors and Weather Elements (*37*).

Weather/Roadway Element	Sensor
Air temperature	Thermometer
Water vapor (dew point or relative humidity)	Hygrometer
Wind speed and direction	Conventional/sonic anemometer and wind vane
Pavement temperature, pavement freezing point, pavement condition, pavement chemical concentration	Pavement sensor
Subsurface temperature/moisture	Subsurface temperature/moisture probe
Precipitation occurrence/type/intensity	Rain gauge, optical present weather detector
Precipitation accumulation	Rain gauge, optical present weather detector, hot-plate type precipitation sensor
Snow depth	Ultrasonic or infrared snow depth sensor
Visibility	Optical visibility sensor, CCTV camera
Atmospheric pressure	Barometer
Water level	Pressure transducer, ultrasonic sensor, or float gauge
Solar radiation	Solar radiation sensor

Atmospheric Sensors

Atmospheric sensors measure various weather conditions including air temperature, barometric pressure, relative humidity, wind speed and direction, precipitation, visibility distance, and cloud cover (an indication of solar radiation). Although these measurements are similar to those provided by NWS, these sensors installed along road sections can help minimize a possibility of spatial discrepancy of observations as well as improve the precision of the measurement.

Temperature Sensor

Air temperature can be measured with liquid, gas, or electrical thermometers. Electrical thermometers, which are commonly used in automated sensor stations, contain metal wires that exhibit increased resistance to electrical current as the temperature rises.

Pressure Sensor

Atmospheric pressure can be measured with mercury or aneroid barometers. Aneroid barometers are typically used in meteorological applications due to their better accuracy. An aneroid barometer contains an aneroid cell – a sealed, flexible metal box or pair of thin circular disks – that expands or contracts as atmospheric pressure changes.

Humidity Sensor

Relative humidity may be defined as the ratio of the water vapor density (mass per unit volume) to the saturation water vapor density, usually expressed in percent. There are many technologies for humidity measurement instruments. Capacitive or dielectric instruments have a material that absorbs moisture, which changes its dielectric properties and enhances its capacitance. Chilled mirror technology uses a mirror that is chilled to the point that moisture starts to condense on it. This temperature is the dew point. With electrolytic technology, moisture is proportional to the current needed to electrolyze it from a desiccant. For resistivity or impedance style sensors, a material absorbs moisture, which changes its resistivity or impedance. In strain gauge instruments, a material absorbs water, expands, and is measured with a strain gauge. Psychrometers, often called wet/dry bulbs, measure relative humidity by gauging the temperature difference between two thermometers, one wet and one dry. The critical specification for these devices is either the humidity or moisture range to be measured or the dew point range. Humidity and moisture accuracy are expressed in terms of percentage of measurement. The dew point accuracy, since this is a temperature reading, is expressed as a variance in temperature output (*40*).

Wind Sensor

Wind vanes are used to determine the direction from which the wind is blowing. The direction is reported in azimuth. Wind speed is typically measured by anemometers with propellers or cups. The number of pulses generated per unit time by the rotation can be converted into the wind speed. Wind speed can also be measured using non-mechanical sensors such as hot wire and sonic anemometers. Hot wire anemometers determine the degree of cooling of a heated metal wire, which is a function of air speed. A sonic anemometer ascertains wind speeds based upon properties of wind-borne sound waves.

Visibility Sensor

Visibility can be reduced by various phenomena including fog, heavy precipitation, wind-blown dust, and grassfire. Visibility can be measured directly with sensors or visually via remote CCTV cameras. Visibility sensors are marketed as a stand-alone unit as well as an integrated unit with other sensors such as weather identifier. The forward-scattering principle is commonly used in visibility sensors. A high-output infrared light-emitting diode (LED) transmitter projects light into a sample volume and light scattered in a forward direction is collected by the receiver. The sensor's output signal is proportional to visibility.

Precipitation Sensor

Precipitation is commonly measured using tipping bucket rain gauges, weighing rain gauges, and rain-intensity gauges. A tipping bucket rain gauge uses a cylinder to collect and funnel rainfall into a small bucket that holds 0.01 inch of water. Once the bucket is full, it tips and empties the water while another bucket is lifted into position under the funnel. Every time a bucket tips, a signal is sent to a recorder. Weighing rain gauges are capable of measuring all types of precipitation without heaters. Precipitation is funneled into a bucket that is weighed to assess amounts. Rain-intensity gauges measure the instantaneous rate of rainfalls using the impacts of precipitation droplets.

Recent technology makes use of an infrared beam to detect and classify various types of precipitation. Infrared beams forming a horizontal cross alter in intensity when exposed to various kinds and quantities of precipitation. The Optic Eye from AerotechTelub registers and analyzes the precipitation situation continuously and can be connected to any host system via a serial port (see Figure 19). It also measures precipitation intensity and classifies rain, snow, sleet, and drifting snow.

Figure 19. Optic Eye Infrared Precipitation Sensor.

Weather Identifier Sensor

A weather identifier sensor identifies the precipitation types (e.g., rain, snow, drizzle). Some also feature the capabilities to detect the occurrence of precipitation and measure the precipitation rate. Technologies such as optical scintillation and capacitive principle have been frequently used by manufacturers. Ability to identify precipitation types gives the road authorities the cause of reduced visibility and necessary information for traffic management and/or road maintenance operations.

Surface Sensors

Surface sensors are the key component that differentiates the RWIS data from those provided by NWS. Many RWIS vendors have continued to develop and refine their pavement sensor products as their key selling point. Relatively little research has been done to objectively and independently evaluate the performance of these different sensors. Recent effort has focused on the issue of communication standards between RPUs and CPUs, primarily because of the proprietary nature of the systems (*39*).

Surface sensors measure pavement conditions (e.g., temperature, dry, wet, ice, freeze point, chemical concentration), and subsurface or soil conditions. In addition to pavement conditions, some surface sensors also collect typical traffic data such as count, speed, and occupancy. There are two basic types of surface sensors – passive and active. Passive pavement sensors are normally buried in the road surface. Changes in their electrical properties are used to determine the temperature and surface conditions. Active sensors work differently. The surface of the active pavement sensor is cooled down to determine at what temperature the surface moisture will freeze, then heats it to repeat the cycle. Another type of active sensor generates and emits a signal and measures the radiation reflected by a targeted surface. If moisture is present on the pavement, microwaves reflect off of the water and the road surfaces. Examples of active pavement sensors are FRENSOR (Figure 20) and ARCTIS (Figure 21) manufactured by AerotechTelub AB and Boschung Mechatronics, respectively.

Figure 20. FRENSOR Active Pavement Sensor.

The pavement sensors can be used for three purposes – detecting, monitoring, and predicting *(36)*. First, they can be used to detect critical conditions or thresholds and then alert responsible agencies. Without sensors, such notification must come from observations from the highway patrol or the traveling public. Second, pavement sensors can be used to monitor current conditions. Monitoring allows a manager to assess the progress of weather events and plan for appropriate actions. Although monitoring and detecting may be similar, detecting is associated with alerting and reacting. The prediction task is to determine what conditions are expected and when they will happen. One important forecast is pavement temperature. Pavement subsurface temperature obtained from a subsurface probe is a critical input for forecasting models.

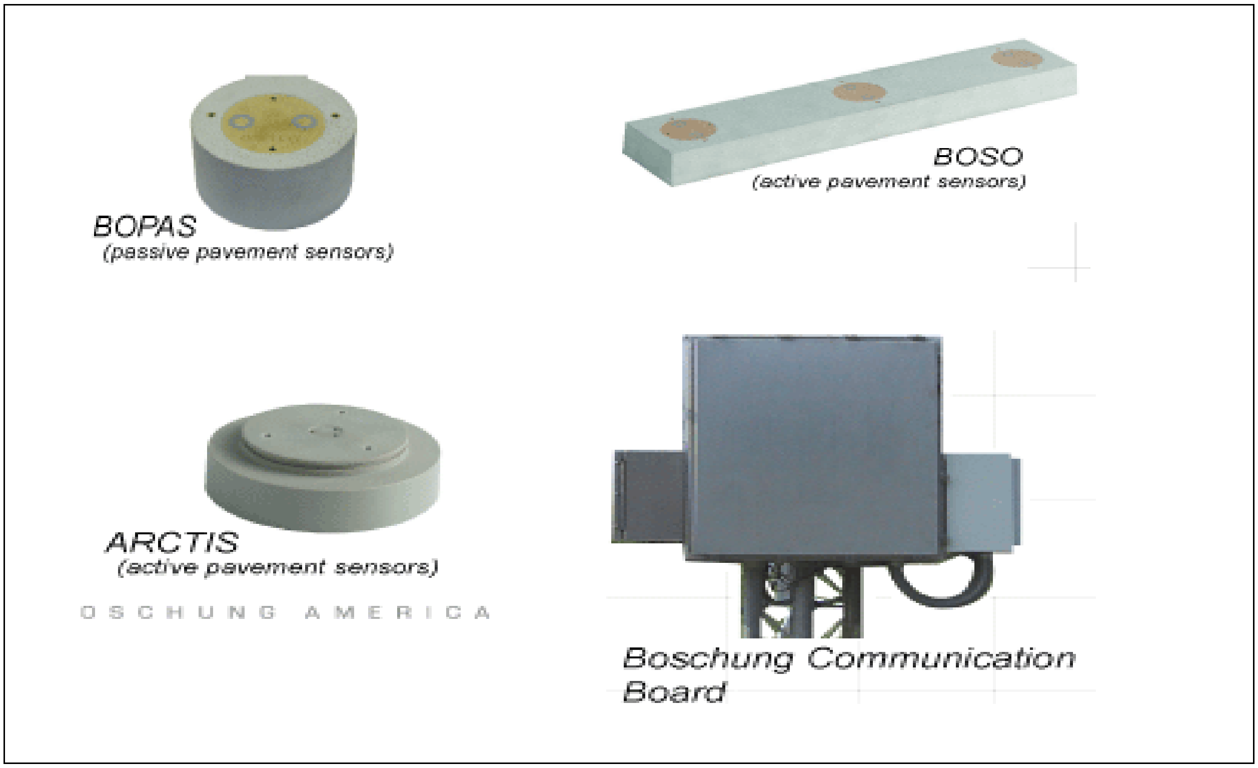


Figure 21. Boschung Pavement Sensor System.

Zwahlen et al. (*39*) conducted extensive product reviews, cumulative cost comparisons, and surveys of users and administrators for the evaluation of roadway/weather system sensor systems for snow and ice removal operations for Ohio Department of Transportation. Pavement sensor products from four major companies – Boschung Mechatronics, Nu-Metrics, Vaisala, and SSI (Surface Systems Inc. is now a subsidiary of Quixote Company) – with RWIS business in the states were reviewed. A comparison between active and passive sensors is summarized in Table 20.

Certain pavement sensors may work well for monitoring purposes but not for predicting purposes. Some vendors also recommend the use of a combination of sensors for best results, e.g., active sensor for predicting freezing point and passive sensor for monitoring pavement temperature. Figure 21 illustrates both passive and active sensors manufactured by Boschung.

Table 20. Comparison between Passive and Active Pavement Sensors.

	Passive Sensors	Active Sensors
Advantages	• Good for measuring pavement temperature and chemical concentration. • Lower cost.	• Better freezing point prediction. • No need to calibrate the sensor for each anti-icing chemical combination. • Knowledge of deicing chemical used is not required.
Disadvantages	• Freezing point must be calculated from chemical concentration, which requires the information about the anti-icing chemical used. • Calibrations are needed for different types of anti-icing chemicals.	• A lower limit on the freezing point that a sensor can detect may be above the actual freezing point. • Sensor reading takes longer time and may be disturbed by vehicles running over the sensor. • Relatively more expensive than passive sensors.

Sensor Placement in the Roadway

A range of opinions exists on where sensors should be located within lanes. Bosselly et al. (*36*) provided a matrix of options for sensor placement within lanes as shown in Table 21. Care should be taken to ensure that the slope of a road at any location is such that there is no drainage onto sensors from the shoulder or the median. Sensors should not be placed on the curve sections.

Table 21. Recommended Placements of Pavement Sensors in Roadways (*36*).

Primary Use of Sensors	Location of Pavement Sensors in Lanes			
	Urban (Commuter Road)		Rural (Non-commuter Route)	
	Multilane Road	Two-lane Road	Multilane Road	Two-lane Road
Prediction	Just outside of outside wheel track of outbound passing lane	Just outside of outside wheel track of outbound lane	Just outside of a wheel track of passing lane	Just outside of a wheel track of either lane
Detection	Just inside of outside wheel track of inbound through lane	Just inside of outside wheel track of inbound lane	Just outside of a wheel track of through lane	Just outside of a wheel track of either lane
Monitoring	Use prediction placement whenever possible			

Hydrologic Sensors

Hydrologic sensors measure water and tide levels to assess flood and storm surge hazards. Four basic types of hydrologic sensors are ultrasonic water level sensors, submersible pressure transducer, stilling wells, and tide gauges.

Ultrasonic Sensor

Ultrasonic water level sensors use acoustics or sound waves to measure the distance from a transducer to the water surface. Figure 22 shows an example of an ultrasonic depth sensor. This same technique can be utilized to measure the snow depth as well.

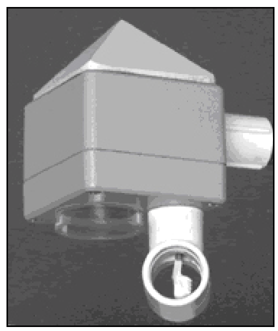


Figure 22. Ultrasonic Depth Sensor.

Submersible Pressure Transducer

The submersible pressure transducer (PT) is designed to measure the water level or water depth. The sensor incorporates a miniature, silicon piezoresistive pressure sensor that features excellent resistance to shock and vibration. A thin tube runs inside the cable and is vented to a box in the standpipe. This tube provides the ambient pressure, allowing the sensor to measure the pressure difference and thus the water level. Although a typical application of PT is to measure stream or bayou level, it can also be used to measure the water level on the roadway. If the PT is not under water, a false reading can occur due to atmospheric temperature and pressure changes.

Stilling Well and Tide Gauge

Stilling wells contain float sensors to measure water levels. A float sensor is typically enclosed in a pipe or cylinder to protect the sensor and allow free movement of water.

Tide gauges may be used to measure storm surge caused by tropical storm. These gauges operate in a manner similar to stilling wells to measure the height of tide.

Mobile Sensing

Mobile sensing is the integration of environmental sensors with vehicle systems. GPS technologies also help facilitate the location identification task. Truck-mounted sensor systems can be utilized to sense pavement conditions (e.g., temperature, friction) and atmospheric conditions (e.g., air temperature).

Friction Measurement Devices

Pavement friction coefficient can be evaluated using deceleration devices, locked wheels, and variable slip systems. Deceleration devices measure a signal generated by a strain gauge when a vehicle brakes. The signal, which is proportional to the deceleration rate, is used to compute the friction coefficient. Friction can also be determined by a locked wheel that is towed behind a vehicle traveling at 30 to 40 mph. Brakes are applied to lock the wheel for 1 second while the resistive drag force is measured.

Remote Sensing

In remote sensing, a detector is located at a significant distance from a target. The sensor is typically part of a radar or satellite system used for surveillance of meteorological and oceanographic conditions.

Weather radar is an example of a remote weather observation. Research is being conducted in Europe on the use of remote microwave sensors installed along roadways to determine pavement temperature and surface conditions. Such observations may prove very useful because in situ measurements represent only a very small surface area, compared to remote measurements area wide. The latter may be more representative of the road environment than those obtainable from the smaller in situ instruments.

SITE SELECTION

Appropriately selecting an ESS site is central to the overall effectiveness of the sensor system and the representativeness of its observations. A recent FHWA document by Manfredi et al. (*37*) provides guidelines on ESS sitings at two different levels – regional site and local site.

Regional ESS Site Considerations

Regional sites are designed to provide road weather observations considered to be representative of the conditions along a given road segment. The regional site can also provide additional data for incorporating into general weather forecast models such as those used by the NWS. The recommendations for selecting an ESS regional site can be summarized as follows:

- ESSs should be located along uniform roadway conditions to minimize local effects such as local heat and moisture sources and wind obstructions.
- ESSs should be sited on relatively flat, open terrain.
- ESSs should be sited on the upwind side of the road based on prevailing wind directions.

Local ESS Site Considerations

Local sites are those that require sensor siting to satisfy a localized weather requirement such as a short segment of roadway or a bridge. Examples of local sites include: (a) localized flooding on low lying road segments, (b) visibility distance where the local environment conditions contribute to poor visibility (e.g., a large local moisture source), and (c) high winds such as those occurring in hurricanes and terrain-induced crosswinds along a confined valley or a ridge top.

Slippery Pavement Conditions

These conditions usually occur in historically cold spots prone to standing water or the development of ice, frost, slush, or snow due to local weather or geographic conditions, e.g., low spot, elevated roadway or bridge, or a predominantly shaded area. In these cases, the purposes of the sensors are to detect or monitor the pavement temperature and conditions.

Pavement sensors that monitor roadway or bridge deck temperature, surface condition, or chemical concentration and freeze-point temperature should be installed. Agencies should also consider specialized locations such as elevated roadways for sensor installation. In areas where road frost is a problem, agencies should also consider mounting a dew point sensor close to the pavement height.

Low Visibility Conditions

Low visibility conditions usually occur in locations where local moisture, smoke, or dust sources exist or in valleys or road depressions that trap cool moist air. Moisture and particulate matter can be man-made, such as factory plume or vehicle traffic, or can occur naturally from a river or swamp, a sandy or dusty area, or drifting snow. Three types of sensors commonly used for these conditions are: (a) visibility sensor to detect a reduction in visibility, (b) thermometer and hygrometer to detect changes in atmospheric moisture and temperature, and (c) wind sensor to measure the speed and direction of the wind.

These sensors should be installed adjacent to the roadway or in areas influenced by local sources of factors contributing to poor visibility. Visibility sensors should be installed such that they represent the atmosphere 6.5 to 10.0 ft above the roadway. The performance of visibility sensors located closer to the roadway may be degraded due to the influence of passing traffic, or snow/ice control practices.

High-Wind Conditions

High winds and strong gusts frequently occur on bridges, confined valleys where channel effects exist, open fields, or on ridge tops. For these conditions, wind sensors should be placed such that they can monitor and detect the onset and duration of high winds and wind gusts at the height most likely to affect vehicle stability, particularly for high-profile vehicles.

To capture hazardous crosswind conditions, a typical wind measurement taken at 33 ft can be supplemented by an additional wind sensor installed at a height of 10 to 16.5 ft – the height of high-profile vehicles. Agencies should take care to avoid siting the wind sensors in the vicinity of moving traffic or in wind shadows. In cases where a wind channeling effect is present, agencies should consider installing sensors at the entry and/or exit areas of these features where wind shear can be experienced.

Water Level Conditions

Flooding usually occurs during or after heavy precipitation, thawing, tidal, persistent counter-flow wind, or storm surge events. Hydrologic sensors including pressure transducers, ultrasonic sensors, and stilling wells can be used to monitor the water levels and flooding conditions.

The pressure transducer can be used to monitor water levels in standing bodies of water such as lakes and reservoirs. The ultrasonic sensor monitors water levels in fast moving streams and rivers. The stilling well and float gauge can be installed in normally dry areas where runoff and precipitation accumulate. For detection of potential flooding on a bridge, it is recommended that sensors be installed on the downstream side in a location with low flow turbulence. These sensors can also be installed near the low lying point of the roadway or adjacent to any road segment prone to flooding.

RWIS COMMUNICATIONS

Communications are required to acquire and disseminate road weather information and data. A study by Boselly et al. (*36*) identified communication components as follows:

- the transmission of data from sensors to RPUs, from RPUs to CPUs, and from CPUs to user work stations;
- the acquisition by value-added meteorological services (VAMS) of weather information, which includes NWS-disseminated data, RWIS data, and data from other remote monitoring sources;
- the communication of road weather forecasts from the forecasters (VAMS) to the maintenance managers who make resource allocation decisions and the information exchange; and
- the dissemination of information to police, road users, and the public.

System incompatibility is an issue encountered by highway agencies implementing RWISs. To improve the interoperability, in 1996, the National Electrical Manufacturers Association (NEMA) teamed with the Institution of Transportation Engineers (ITE) and the AASHTO to develop the National Transportation Communications for ITS Protocol (NTCIP). The adoption of NTCIP ESS standards will allow for an open-systems approach among ESS equipment, which is expected to result in lower deployment and equipment costs.

The TxDOT ESS Concept of Operations (COO) defines a high-level overview of the characteristics and capabilities of future TxDOT ESS subsystems (*40*). The operation of an ESS can be described by defining the message transactions that take place between the ESS and a TMC. The message transactions occur in two broad categories: (a) ESS description transaction and (b) ESS data transactions.

The TxDOT ESS Software Requirements Specification (SRS) defines the requirements for the TxDOT ESS system, which are classified into five categories: (a) interface requirements, (b) functional requirements, (c) performance requirements, (d) computer resource requirements, and (e) operational requirements (*41*).

RWIS SYSTEMS IN TEXAS

Benz et al. (*42*) document the ESS system's capabilities, types of flooding, flood events, and equipment reliability. Figure 23 depicts Houston's environmental monitoring system and interrelated components. The environmental sensors at each site gather the data and relay the information to the base station via radio transmitter. This information is stored into the Harris County Office of Emergency Management database, where quality control checks are conducted and alarm thresholds are checked.

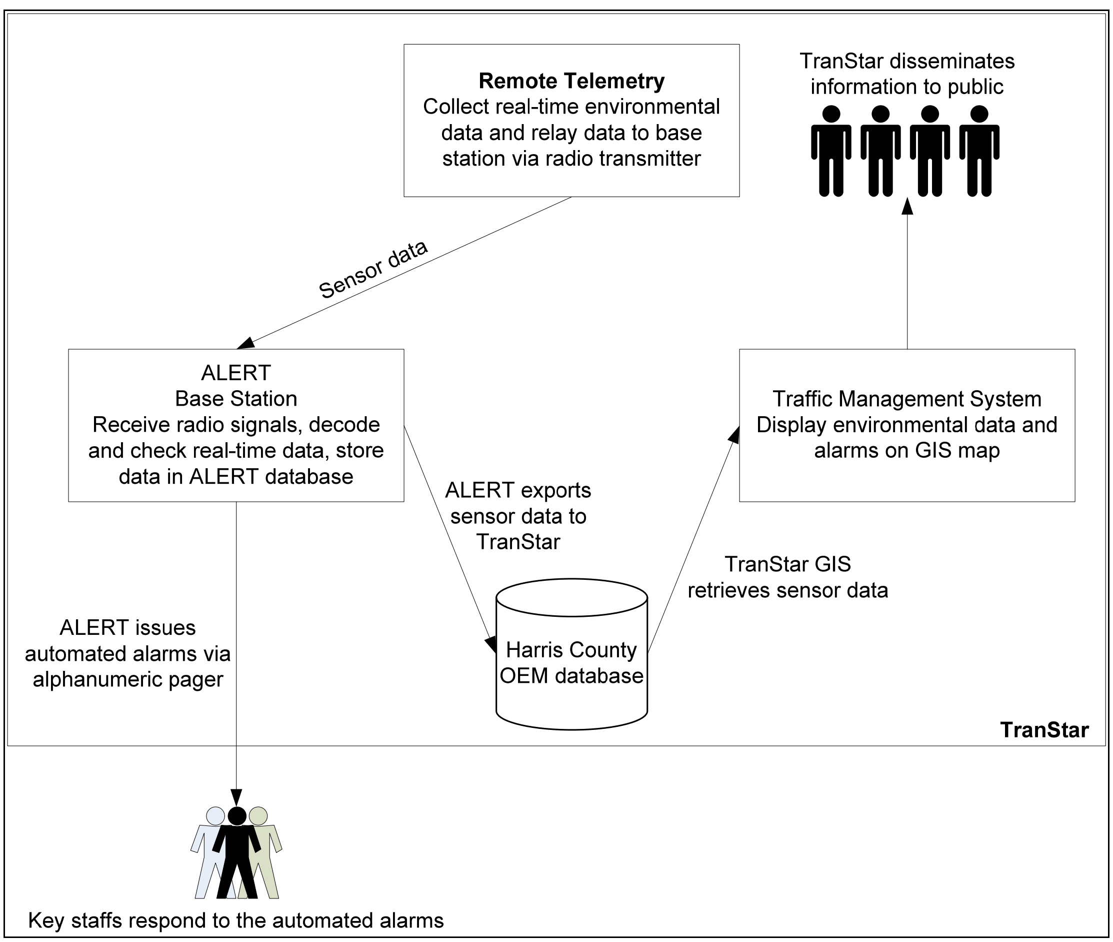


Figure 23. Houston Environmental Monitoring System and the Interrelated Components (modified from *42*).

A rainfall rate of 2 inches per hour is used by Harris County OEM as an indicator of street flooding. Houston ESSs are stand-alone units, which do not need a power or a phone line to transmit the sensor data. All communications are carried out via battery-powered radio transmitters that are charged by a solar panel.

The interim operations plan for flooding events was developed as shown in Figure 23. The plan describes the criteria and threshold that should be used for flooding events. Some of the key points noted in the plan development are as follows:

- The roles and duties of each agency should be defined, as well as any internal and external communication required.
- Redundancy should be in place so that a missing link in the chain would not impact the operation.
- Automation of the system would greatly improve the use and the effectiveness of the plan.

Sensor location is crucial for an efficient detection of localized flooding. Several example cases in which inappropriate sensor placement hampered the system efficiency were mentioned in the study. Transmitter, battery, solar panel, pressure transducer, and rain gauge failures were discussed in the study from the ESS maintenance viewpoint. The average maintenance period is about 114 days and the average time between non-scheduled services is 49 days.

MODELING THE IMPACTS OF WEATHER EVENTS ON FREEWAY TRAFFIC OPERATIONS

Weather events can impact traffic flows on a day-to-day basis. From the operational viewpoint, weather events can decrease travel speeds and increase travel time delays. From the safety viewpoint, weather events can increase the likelihood of accidents on roadways. The objective of this study is to assess and quantify the operational and safety impacts of weather events on freeways.

The scope of this study is defined as follows:

- Location: Austin weather and freeway traffic data;
- Operational impacts: effects on travel speed and capacity; and
- Safety impacts: effects on speed variance.

We used the Austin freeway traffic and weather data in the analysis. Literature indicated a wide range of weather impacts depending on locations and types of weather events. In addition, different driver behaviors and traffic compositions could potentially be significant contributing factors to the differences in the impacts. Texas drivers are less likely to be accustomed to driving on snow-covered pavement, and trucks represent a significant portion of traffic on the roadway. The use of Austin data helped us explore if and how weather events impact traffic conditions from both operational and safety perspectives in Texas.

For operational impacts, we examined the effects of weather events on travel speed and capacity on freeways. Safety impacts, however, are more difficult to measure as it would require years of observation to gather sufficient crash data. Therefore, we used a surrogate safety measure known as a speed variance. Speed variance or the coefficient of variation in speed (CVS) was found to be a promising precursor of crashes in a number of previous studies (*43,44,45*). None of the past studies evaluated safety impacts of weather events through the use of surrogate safety measures.

In this section, we first review the literature related to analyses and findings of impacts of weather events on freeways and arterials. For instance, we review if and how poor visibility condition and rainfall can cause a reduction in travel speed and an increase in speed variance. We also attempted to quantify if and how traffic conditions were affected by a combination of factors. Then, we discuss the data descriptions and the methodology used in this study. Results and findings from the analysis are then presented. The discussions of results and future research opportunities conclude the paper. Freeway operators can use this information about operational and safety impacts during weather events as a decision support tool in deploying appropriate strategies to improve traffic flow and mitigate the potential of freeway accidents.

PREVIOUS WORK

Ibrahim and Hall (*46*) studied the impacts of adverse weather conditions on the flow-occupancy and speed-flow relationships. The data used in the analysis were obtained from the Queen Elizabeth Way Mississauga freeway traffic management system. Two detector stations that met the following criteria were selected for the study: (a) trap detectors, (b) outside the vicinity of ramp or weaving sections, and (c) satisfactory data quality. However, the authors did not mention any attempt to exclude any incident-related impacts on traffic operations. Regression analyses were calibrated to the selected data sets using indicator variables to represent different adverse weather conditions. A quadratic functional form was used to calibrate the flow-occupancy relationship, while a linear functional form was used to estimate the speed-flow relationship. Only uncongested regimes were examined in the study. The analyses were conducted using both 30-second and 5-minute aggregated loop detector data. The results were found to be similar for both intervals except for the rainy condition, where the difference in slope of the flow-occupancy function is undetectable for 5-minute aggregated data.

Ibrahim and Hall (*46*) concluded that adverse weather conditions reduce the slope of flow-occupancy function and cause a downward shift in the speed-flow function. For example, light rain and light snow can cause a drop in free-flow speed by 1.2 and 1.9 mph (2 and 3 km/hr), respectively. Heavy rain and heavy snow, on the other hand, can reduce the free-flow speed by 3 to 6 mph (5 to10 km/hr) and 24 to 31 mph (38 to 50 km/hr), respectively. Based on a limited sample data set, maximum flows were observed to reduce by 10 to 20 percent during heavy rain condition and 30 to 48 percent during heavy snow.

Brilon and Ponzlet (*47*) examined the non-traffic impacts on speed-flow relationships on German autobahns. Traffic volume, traffic mix, and temporal factor were considered as fundamental influencing factors, while changing environmental factors such as daylight, weather conditions, and daily and seasonal variations were the main focus of the study. Based on the analysis of variance (ANOVA) models and separation of different sample data sets, the authors concluded that darkness and wet roadway conditions can cause average reductions of speeds by about 3.1 mph (5 km/hr) and 6.2 mph (10 km/hr), respectively. Lower average speeds were also detected during predominantly leisure traffic such as Sundays or the summer vacation season.

Based on the estimated ANOVA model, Brilon and Ponzlet (*47*) reconstructed speed-flow diagrams for free flow and partly dense traffic regimes under varying environmental conditions based on Greenshield's model. Space-mean speed can be derived as a function of multiple variables as follows:

$$v = \frac{a}{2} + \sqrt{\frac{a^2}{4} + b \cdot q} \tag{1}$$

with

$$a = \hat{\mu} + \hat{\alpha}_{YOC} + \hat{\beta}_{MOY} + \hat{\gamma}_{DOW} + \hat{\varepsilon}_{LD} + \hat{\zeta}_{DW} - x_1\hat{k} + x_2\left(p - \hat{p}\right) + \hat{\delta}_{CSL} \tag{2}$$

and

$$b = x_1, \tag{3}$$

where,

v = space-mean speed,
q = traffic flow (veh/hr),
$\hat{\mu}$ = general mean,
$\hat{\alpha}_{YOC}$ = effect of year with 3 levels (1991, 1992, 1993),
$\hat{\beta}_{MOY}$ = effect of month with 12 levels,
$\hat{\gamma}_{DOW}$ = effect of days of week,
$\hat{\varepsilon}_{LD}$ = effect of daylight,
$\hat{\zeta}_{DW}$ = effect of weather conditions with 5 levels,
$\hat{\delta}_{CSL}$ = effect of site location,
$\hat{k}$ = traffic density (vehicles/km),
x_1 and x_2 = regression coefficients, and
$\hat{p}$ = percent trucks.

In a more recent study, Agarwal et al. (*48*) examined the impacts of adverse weather on freeway capacities and operating speeds on urban freeway segments in the Minneapolis/St. Paul, Minnesota, area using a data set from January 2000 to April 2004. Traffic data were obtained from loop detectors for every 30-second interval, while weather data were obtained from automated surface observing systems (ASOS) at nearby airports. The research found that the quality of weather data obtained from RWIS sensors was not appropriate for the analysis. Speed data, however, must be estimated since only single-loop detectors have been installed in the studied network. This may be a potential source of errors in this study. The authors assumed a 10-minute interval to collect and average weather and traffic data for the similar time periods, as previous research indicated that time intervals between 5 and 15 minutes are appropriate to compute hourly flow rates (*49*). Freeway capacities were estimated using the maximum observed throughput approach. The operating speeds were estimated from a weighted average of speeds by flow rates between 45 mph and 80 mph.

The authors found that the rain and snow events can cause statistically significant reductions in freeway capacities and operating speeds. The average capacity reductions for trace, light, and heavy rain are 1 to 3, 5 to 10, and 10 to 17 percent, respectively. The corresponding figures for operating speed reductions were 1 to 2, 2 to 4, and 4 to 7 percent. For the snowfall events, the reported reductions in capacities were 3 to 5, 6 to 11, 7 to 13, and 19 to 27 percent for trace, light, moderate, and heavy snow, respectively. The corresponding figures for reductions in operating speeds were 3 to 5, 7 to 9, 8 to 10, and 11 to 15 percent, respectively.

For urban arterials, traffic flow rates were found to be 6 to 30 percent lower than those under normal conditions, depending on road conditions and time of day. Speed reductions under inclement weather conditions ranged from 10 to 25 percent in rainy, wet pavement conditions and from 30 to 40 percent with snowfall and snowy/slushy pavement (*50,51*).

Based on existing literature, Goodwin (*52*) reported weather impacts on travel time delay and start-up delays on arterial roadways. Travel time delay increased by 11 percent in wet pavement conditions, and by more than 12 percent in the presence of precipitation, low visibility, slippery pavement, or high winds. Travel time increased by as much as 50 percent during extreme weather conditions such as heavy snowstorms. The corresponding figures for coordinated signal systems were also reported.

Several studies concluded that weather-related signal timing plans can benefit traffic operations on arterial roadways during inclement weather conditions (*50,51,53*). Past studies found that weather-related signal timing can increase speeds by 12 percent, decrease travel times by 13 to 18 percent, reduce average delay by 8 to 23 percent, and decrease the number of vehicle stops by 6 to 9 percent.

Past studies revealed that impacts on traffic operations during weather events depend on a number of factors such as locations and types of weather events. Speed-flow-occupancy relationships were also found to be affected by weather events. However, none of the past studies evaluated the impacts of weather events on real-time safety measurements through the use of surrogate safety measures. In this study, we considered localized incident-free Austin loop detector data under a wide range of weather conditions. We identified and quantified the impacts of different weather conditions on traffic from both operational and safety aspects. Speed variation is one measure of safety that we can observe in real-time and use to support the selection of appropriate preventive strategies to mitigate the likelihood of freeway accidents during weather events.

DATA

There are two sources of data required for this analysis: traffic data and weather data. Austin loop detector data, which include volume, occupancy, speed, and percent truck for trap detectors, were archived at 1-minute intervals. We selected detector stations on Loop 1 in the vicinity of the Camp Mabry weather station (see Figure 24). The detector stations further from the selected ones were not considered in the analysis to avoid spatial discrepancies in weather conditions.

Weather records at the Camp Mabry station were obtained from climatological data service provided by the National Climatic Data Center (NCDC) and can be accessed online (*54*). Weather data are usually archived on an hourly basis. However, archival frequencies may increase during special weather types such as thunderstorm or heavy fog.

Weather archive data contain both qualitative and quantitative fields. Some fields are ordinal-qualitative. For example, a weather type "TS" would represent moderate thunderstorm while TS+ and TS– indicate heavy and light thunderstorm, respectively. In addition, there can be a combination of weather types. For instance, if a light thunderstorm and a haze are occurring at the same time, the weather type record will be "TS– HZ." In order to perform the analysis, these text formats must be recoded as indicator variables, and a combination of weather types must be split into a set of single indicator variables.

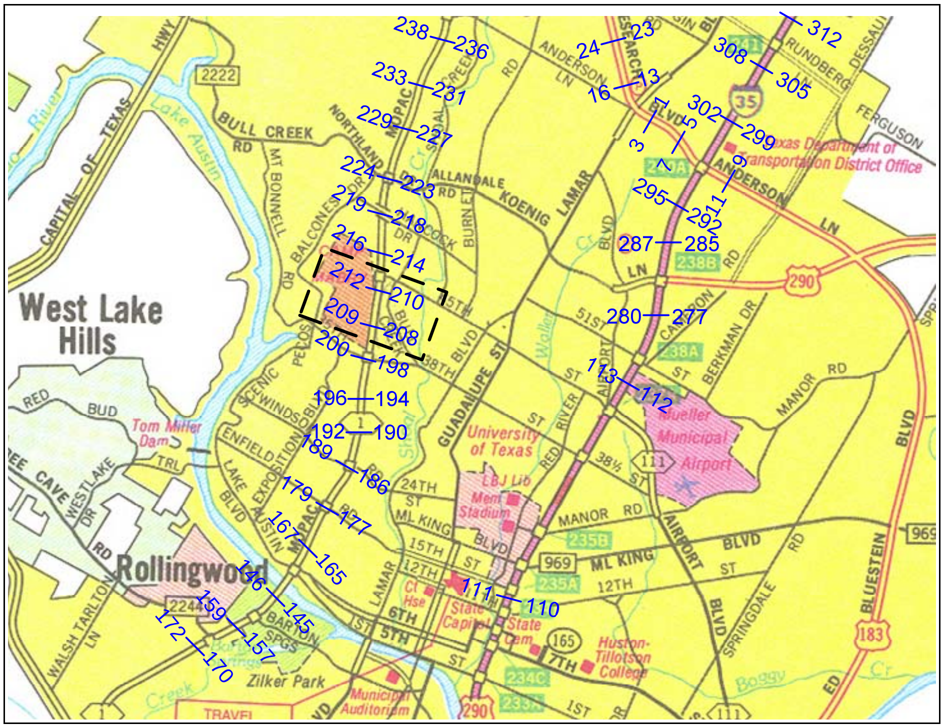


Figure 24. Selected Detector Stations on Mainline Loop 1 in Austin, Texas.

Data Descriptions

The following criteria were applied to the loop detector data to select the data set for the analysis:

- We identified four detector station IDs in the vicinity of the Camp Mabry weather station for the preliminary analysis, which are 208, 209, 210, and 212.
- We used incident-free loop detector data in 2003 in the analysis. Incident logs from Austin TMC were retrieved and used to remove incident traffic conditions from the sample. The entire day of loop data were removed if an incident was reported to avoid the potential errors from the incident logging procedure (e.g., delays between incident occurrence and reported times, clearance times, etc.). Sixty-four days of incident-affected loop data were removed in this step. Note that recurrent congestion was not considered as an incident.

The filtered loop data were then matched with weather records. We used 1-hour window checking periods to determine whether the weather conditions for each detector record can be identified. In other words, for each loop detector observation, the weather conditions within 30 minutes before and after the detector time stamp were searched and the nearest weather record, if found, was identified as representative of weather conditions at that detector time stamp; otherwise, the detector record was denoted as unidentified weather condition and thus excluded from further analysis.

For the purpose of our analysis, we classified weather conditions into two major types:

- Normal weather conditions: visibility greater than 5 miles, no wind gust, and no specific weather type reported.
- Irregular weather conditions: any conditions that differ from normal weather conditions.

The direct use of 1-minute loop data in the analysis can be problematic in the analysis due to excessive noise in the data set. To mitigate this problem, a 15-minute averaging interval was applied to the loop data. We examined the plots of speed-flow-occupancy relationships (see Figure 25 and Figure 26) using 1-minute versus 15-minute loop data to ensure that the use of the averaging interval, while reducing the fluctuations, still captured basic traffic flow properties. A visual examination of 15-minute versus 1-minute plots indicates that the use of the 15-minute average interval still captures basic traffic flow properties.

Computed Traffic Measures

We applied the 20 percent rule to screen and remove invalid intervals for the calculation of 15-minute average data. In other words, if any of 15 consecutive 1-minute loop data contains more than 20 percent of missing or erroneous detector readings, the entire 15 consecutive observations was discarded. In the current implementation of loop detector system in Austin, erroneous detector observations are checked at the system control unit (SCU) level and then flagged as -1.

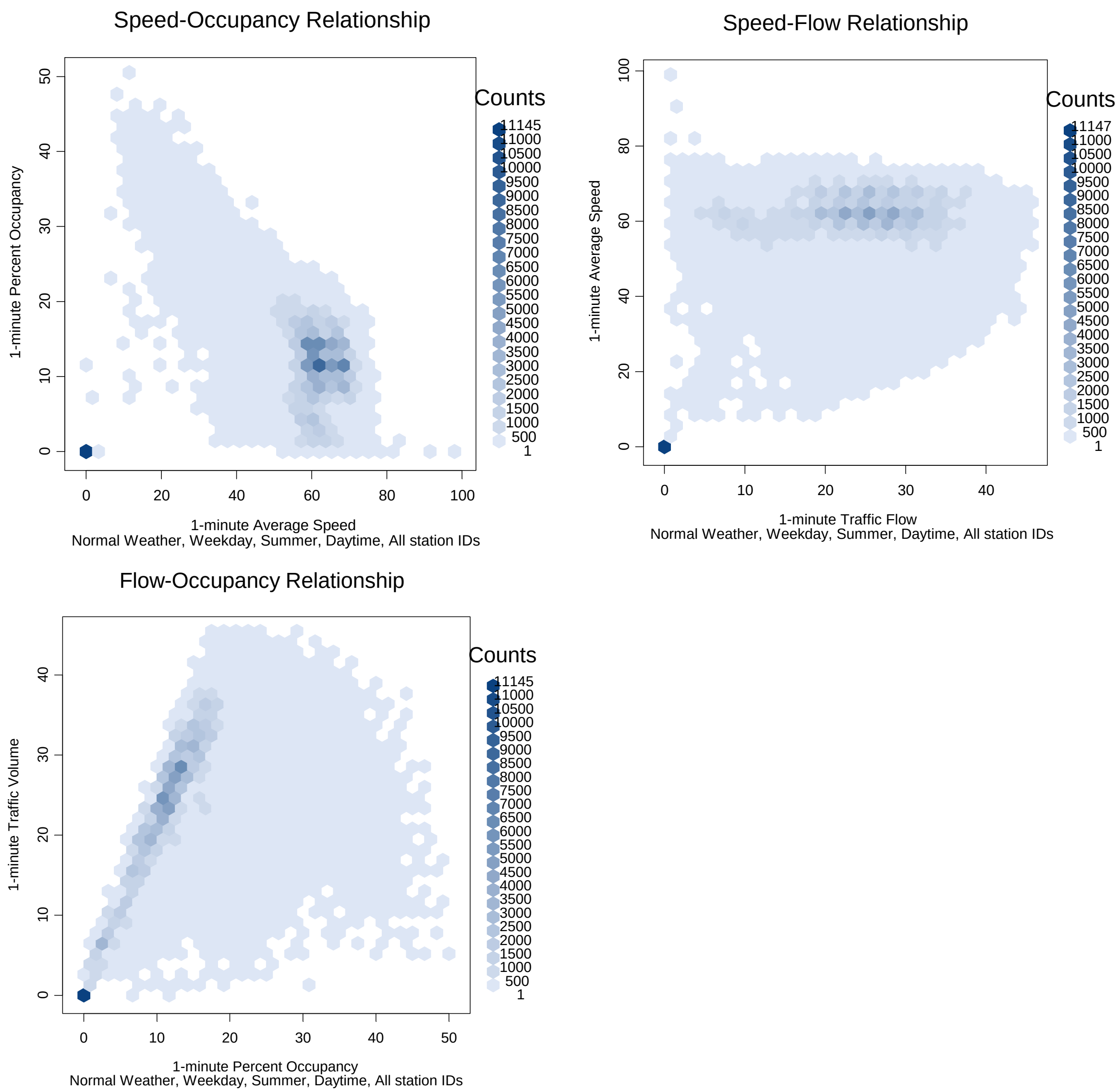


Figure 25. Flow-Occupancy-Speed Relationships of 1-minute Loop Data.

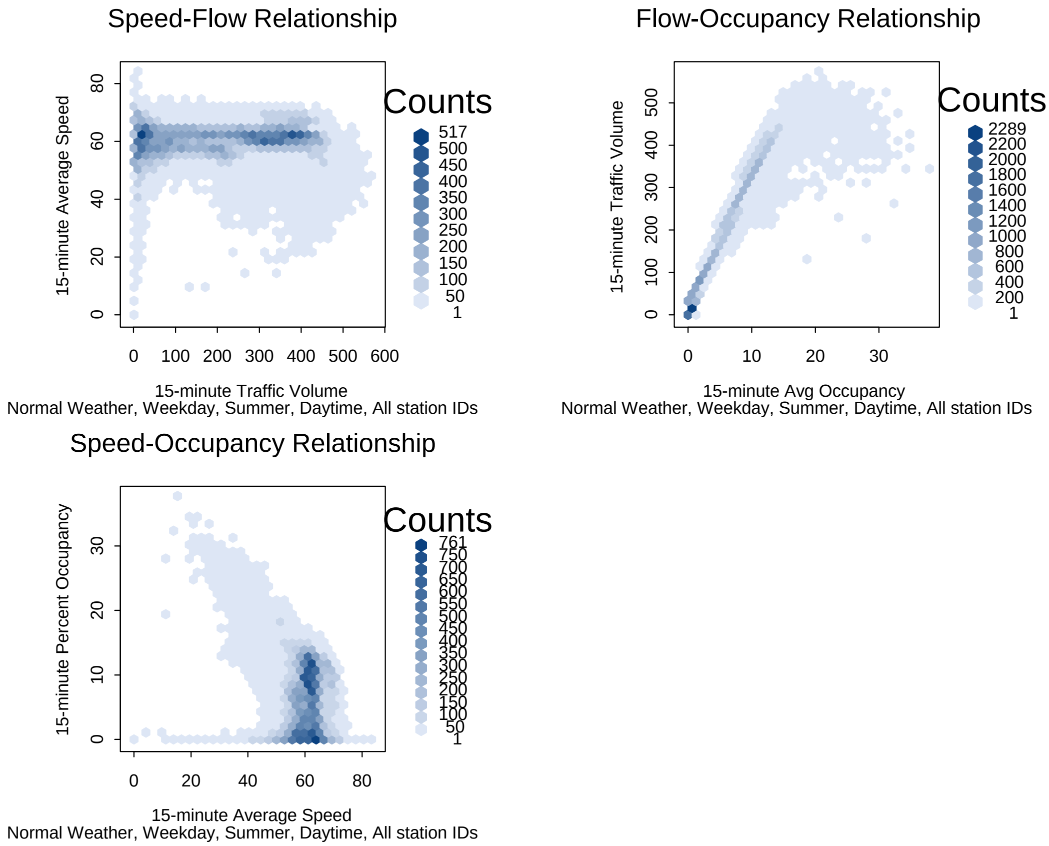


Figure 26. Flow-Occupancy-Speed Relationships of 15-minute Loop Data.

Using data from each individual loop detector, we calculated a lane-by-lane average flow rate, average occupancy, weighted average speed, and coefficient of variation in speed using a 15-minute interval. In the case where there were less than 15 observations in the 15-minute interval, a 1-minute average flow rate was first computed using all the available observations in that interval and then converted to a 15-minute flow rate. The calculation of average 15-minute flow rate can be expressed as:

$$\overline{q} = \frac{\sum_{i=1}^{N} q_i}{N} \times 15 \tag{4}$$

where,

q_i = 1-minute volume count of i^{th} interval, and

N = number of 1-minute intervals available in a 15-minute averaging window.

The average occupancy is calculated as:

$$\overline{o} = \frac{\sum_{i=1}^{N} o_i}{N} \tag{5}$$

where o_i = 1-minute average percent occupancy.

The weighted average speed is calculated as:

$$\overline{v} = \frac{\sum_{i=1}^{N} q_i v_i}{\sum_{i=1}^{N} q_i} \tag{6}$$

where v_i = 1-minute weighted average speed of i^{th} interval.

The weighted average speed has an advantage over the arithmetic mean in that zero-count intervals are not used in a calculation, thus avoiding underestimating mean values. The weighted average speed better describes the true fluctuation of vehicles' speed over time, particularly during nighttime, where there is a preponderance of zero-count intervals.

The CVS is a measure of the amount of fluctuation in traveling speeds. Past studies indicate that a breakdown in freeway traffic flow significantly increases the CVS and, thus, the likelihood of accidents (*43,44,45*).

Because a speed observation can be zero when there is no vehicle, the computation of CVS can be done in many variations. The first method is to compute the CVS using the 1-minute average speeds over a 15-minute interval while each interval is weighted equally. In this manner, zero-count intervals, which are not uncommon at night, increase the values of CVS. In other words, CVS may be high because zero-count intervals can cause abrupt changes in speed values. The second method is to compute the CVS as in the first case, but with each interval weighted by volume counts. Mathematically, this can be expressed as:

$$CVS = \frac{\sigma_{v_i}}{\overline{v}} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N} q_i \left(v_i - \overline{v}\right)^2}}{\overline{v}}. \tag{7}$$

Other measures such as standard deviations of volume and occupancy were not computed since earlier study on these indicators as surrogate safety measures did not find results encouraging (*55*).

Factors

We classified factors that may affect freeway traffic operations and safety into four categories: (a) temporal dependency, (b) spatial dependency, (c) weather conditions, and (d) traffic characteristics. It should be noted that there exist factors that we were unable to capture in the analysis due to difficulties in observations or errors in data sources. These factors alternatively can be viewed as a part of the error component in our analysis approach discussed in the subsequent section.

Examples of temporal-dependent factors considered in this study are:

- peak versus off-peak period,
- daytime versus nighttime, and
- days of week.

Spatial-dependent factors are those related to study locations. Examples of this type of factors are:

- geometric characteristics (e.g., presence of curvature, presence of ramps, etc.),
- traveling direction, and
- presence of work zones.

Weather conditions are dynamic and can be predicted with a high degree of accuracy only within a short period of time. Due to a multitude of different weather possibilities, only prevailing weather conditions in Austin were considered in this study. Rare events such as snowfalls were excluded due to inadequate sample size. Three weather-related elements considered in this study are:

- Prevailing weather types as observed by the permanent weather station: rain (RA), thunderstorm (TS), fog (FG), and haze (HZ).
- Visibility conditions reported in statute miles ranging from 0 to 10+ miles. We further classified the visibility condition into four groups to facilitate our analysis as follows: good (4+ miles), fair (1+ to 4 miles), poor (½ to 1 mile), and very poor (less than ½ mile).
- Wind conditions specified by wind speed (mph) and presence of wind gust. High-wind condition may affect the operation of high-profile vehicles.

Traffic characteristics could be either vehicle-based such as traffic composition, or driver-based such as drivers' behaviors or socioeconomic characteristics. We considered only the former type in this study. Truck percentage as recorded by loop detectors was originally included in the analysis; however, it was later excluded due to difficulty in validating the accuracy of percent truck observation.

In summary, the environmental and weather data were discretized into 15-minute intervals corresponding to loop detector data. Then, adjustment rules were applied in order to reconcile certain factors that can vary within the interval. The factors incorporated into the analysis conducted in this study as well as their adjustment rules are listed below:

- visibility (in statute miles): observed minimum visibility is used if visibility conditions change during the 15-minute interval;
- wind speed (in mph): ranging from 0 to 20 mph. Maximum sustained wind speed was used if wind speeds vary during the 15-minute interval;
- presence of wind gust – a short duration of wind speed above 20 mph;
- presence of rainfall;
- presence of thunderstorm;
- presence of fog;
- presence of haze;
- daytime versus nighttime;
- seasonal factor (fall, winter, spring, and summer);
- day of week; and
- traffic direction (northbound versus southbound).

Data Quality

We performed a quality check on the loop detector data by visual examination of volume-occupancy-speed relationships detector-by-detector as well as station-by-station. It was found that southbound detectors are undercounting traffic volume; therefore, only northbound detector stations remain for the analysis. Detailed examination of the plots further revealed a discrepancy in the detector data from all the selected stations except for the station ID 210. As a result, the detector data from the station ID 210 were used for all the analyses in this study. It should be noted that data from other detector stations are also available but cannot be included in the analysis, as we required the studied location to be in the proximity of the Camp Mabry weather station to avoid any spatial irregularities in weather conditions observed at the weather station vis-à-vis the detector station.

METHODOLOGY

This section describes the methodology used in this study to relate and quantify the impacts of weather and environmental factors on freeway traffic operations.

Overview

We used the analysis of covariance (ANCOVA) to assess and quantify important environmental and weather factors. ANCOVA is an analytical technique that combines features of ANOVA and regression. The idea of ANCOVA is to augment the ANOVA model containing the factor effects with one or more additional quantitative variables that are related to the response variable (*56*). In this study, we used a combination of ANCOVA and regression models to analyze the weather and environmental impacts on freeway operations as observed through three important variables:

- speed,
- capacity, and
- speed variation – as measured by CVS.

First, we set up an ANCOVA model to screen for important factors that have statistically significant impacts upon freeway operations. Then, we applied a regression approach to calibrate the speed estimation model based on the results of ANCOVA. Using the regression results, we derived an equation to estimate a freeway capacity under specific weather and environmental conditions based on Greenshield's relationships.

Finally, we calibrated a separate ANCOVA model to examine important factor effects on the speed variation. Speed variation has been consistently reported as a potential precursor of freeway accidents (*43,44,45*). Because it is impossible to measure the effects of weather and environment through changes in the expected number of crashes in real-time, we selected CVS as a surrogate safety measure in this case.

Data Selection

A visual examination of speed-flow-occupancy relationships suggested that a 15-minute interval is adequate for the analysis. In addition, preliminary functional relationships of speed-flow-occupancy were examined based on these plots. In order to avoid the effects of flow breakdowns, we used these plots to further classify the traffic into uncongested and congested traffic regimes. Only the uncongested traffic regime was used in the analysis since breakdown traffic is prone to irregular patterns and, thus, may not well reflect the impacts of weather and environmental conditions.

Validity Check and Traffic Regime Classification

Based on typical traffic properties at the selected detector station, the following set of criteria must be satisfied for loop detector data to be considered valid:

- weighted average speed ≤ 85 mph,
- traffic flow rate ≥ 60 vphpl or 1 veh/min, and
- occupancy ≥ 1 percent.

It should be noted that the above conditions are likely to be met within a 15-minute duration in a normal traffic condition if loop detectors are working properly. The detector data that fail to satisfy any of the above criteria were designated as invalid and were excluded from the analysis.

Next, we classified detector observations into an uncongested traffic regime if one of the following conditions was met:

- weighted average speed ≤ 50 mph and average occupancy ≥ 15 percent, and
- traffic flow rate ≥ 2,000 vphpl.

Figure 27 shows speed-flow-occupancy relationships of valid detector data for all regimes versus the uncongested regime. The top two figures show the plots of the valid detector for both congested and uncongested regimes. The bottom two figures show the valid detector observations in the uncongested regime using the proposed criteria. Note that all the valid detector observations are shown in Figure 27 regardless of weather and environmental factors.

Linearity of Speed-Occupancy Relationship

A speed-occupancy relationship was plotted using the selected data set to examine appropriate functional forms for the model (see Figure 28). A nearly linear speed-occupancy relationship suggested that observed occupancy values can be used as a concomitant variable in an ANCOVA model to reduce the variability of the error terms encountered in the basic ANOVA model. Speed-occupancy linearity has been widely reported in the literature (*57*).

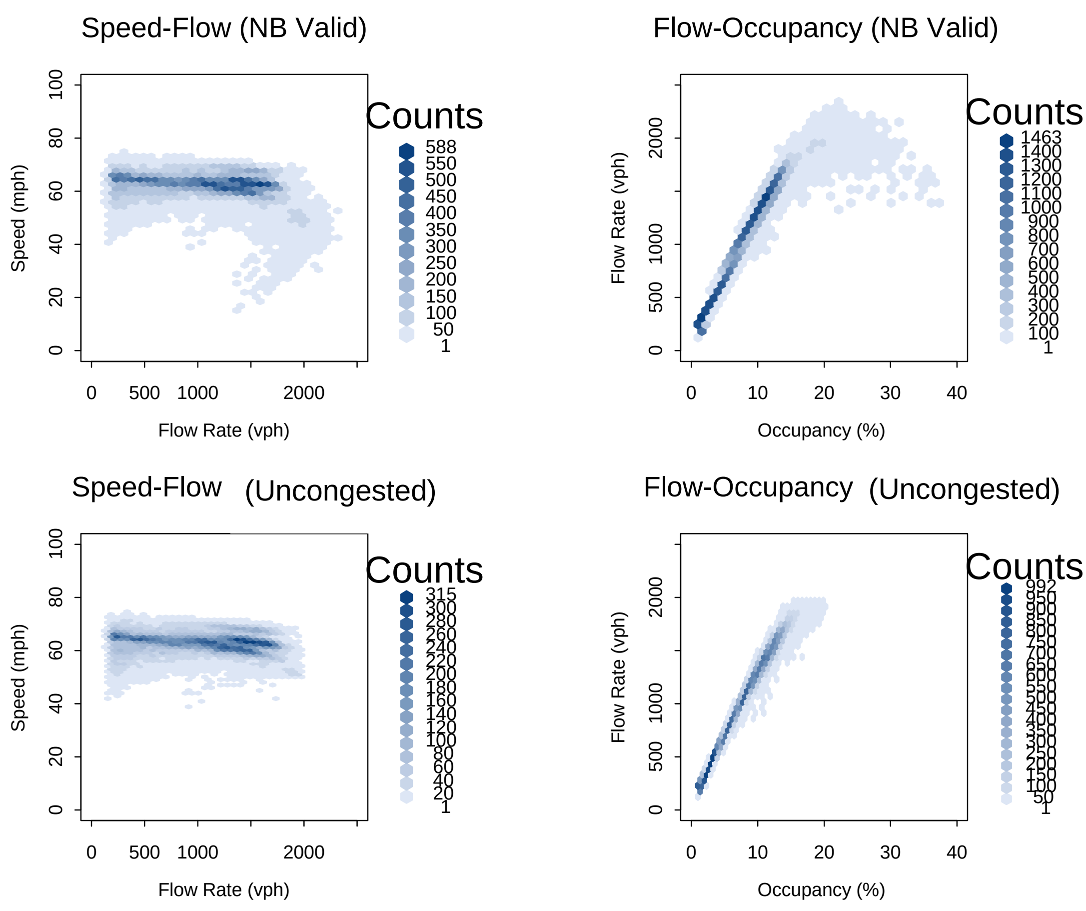


Figure 27. Flow-Occupancy-Speed Relationships of Selected Data.

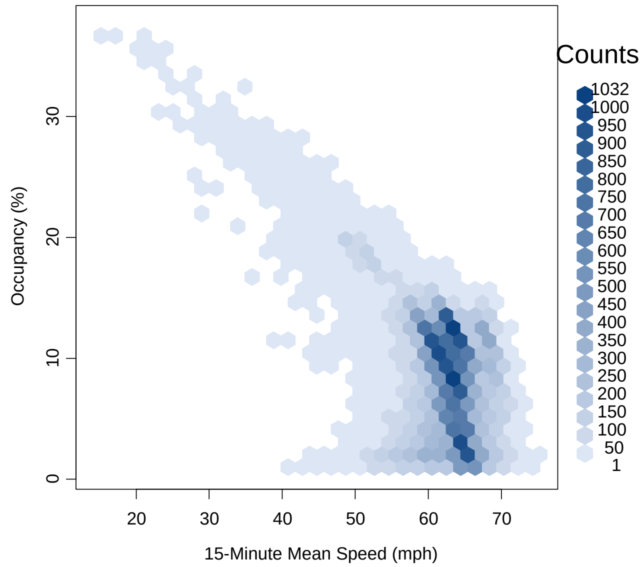


Figure 28. Relationship between Speed and Occupancy.

Descriptive Statistics

Examples of descriptive statistics and distributions for selected computed traffic parameters and weather/environmental factors are summarized in Table 22.

Descriptive statistics and distributions of variables considered in this study were examined to ensure that: (a) the data range falls within reasonable values, (b) the variable being analyzed was not under- or overrepresented, (c) the sample size is adequate, and (d) there exists sufficient variation in the analyzed variables. The examination of statistics in Table 22 did not reveal any discrepancies in the sample and thus allowed us to proceed with the analysis using the selected data set.

ANALYSES AND RESULTS

First, we examined the impacts of weather and environmental factors on traffic operations as observed through changes in speeds and capacities. Then, we evaluated and quantified the safety impacts using speed variation. Calibrated models and results from the analyses are presented in this section.

Table 22. Examples of Descriptive Statistics and Distributions of Selected Variables.

Quantitative Variable	Min.	Median	Mean	Max.
15-Minute Volume (per lane)	31	281	265	580
Average Occupancy (%)	1.00	8.47	8.34	37.33
Weighted Average Speed (mph)	15.19	63.06	62.29	74.29
Std. Deviation of Speed (mph)	0.66	2.20	2.90	32.27
Coefficient of Variation in Speed	0.01	0.04	0.05	0.68
Visibility (miles)	0.10	10.00	9.32	10.00*
Wind Speed – No Gust (mph)	0.00	0.00	1.58	19.00
* Limited by capability of visibility sensor of a weather station				

Distribution of Indicator Variable	1: if Yes	0: if otherwise
Presence of Wind Gust	4928	35,379
Presence of Rain	1329	38,978
Presence of Thunderstorm	400	39,907
Presence of Fog	183	40,124
Presence of Haze	842	38,465
Presence of Daylight	18,892	14,152

Distribution of Qualitative Variables

Detector Location	Left Lane	Middle Lane	Right Lane
	9440	15,718	15,149

Seasonal Factor	Winter	Spring	Summer	Fall
	7718	12,333	15,114	5141

Days of Week	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.
	4535	4270	4874	4676	5233	8602	8117

Analysis of Mean Speed

We conducted the analysis of covariance in order to screen for statistically significant factors affecting freeway operating speed and then calibrated a regression model in order to quantify their effects.

Analysis of Covariance

A nearly linear speed-occupancy relationship suggests that average occupancy can be treated as a covariate or a concomitant variable in the covariance analysis. As a result, the multifactor covariance model of mean speed with fixed effects can be set up as follows:

$$v_{ijklmnpqr} = v_{.........} + O_{ijklmnpqr} + \alpha_i + \beta_j + \gamma_k + \delta_l + \eta_m + \phi_n + \lambda_p + \pi_q + \theta_r \tag{8}$$

where,

$v_{ijklmnpqr}$ = 15-minute weighted average speed (mph);

$v_{.........}$ = overall mean speed (mph);

$O_{ijklmnpqr}$ = 15-minute average occupancy (%);

α_i = effect of detector location: left, middle, and right lane;

β_j = effect of days of week: weekdays (Tuesdays to Thursdays), Mondays, Fridays, and weekends;

γ_k = effect of seasons: winter, spring, summer, and fall;

δ_l = effect of visibility conditions: good (4 miles or more), fair (1 mile to 4 miles), poor (½ mile to 1 mile), and very poor (less than ½ mile);

η_m = effect of presence of thunderstorm;

ϕ_n = effect of presence of rain;

λ_p = effect of lighting condition: daytime and nighttime;

π_q = effect of foggy condition; and

θ_r = effect of haze condition.

The covariance analysis results are presented in Table 23. All the factors considered were found to be statistically significant at $\alpha = 0.05$ except for the presence of haze. Several meaningful interaction effects were also examined; however, they were not found to be statistically significant at $\alpha = 0.05$.

Table 23. Results of Fixed Effect Multifactor Covariance Analysis of Mean Speed.

Factor Description	DF	Sum of Sq	Mean Sq	F Value	P-Value
15-Minute Average Occupancy	1	164,039.6	164,039.6	11,109.85	0.000
Detector Location	2	70,292.5	35,146.2	2380.34	0.000
Day Groups	3	2576.6	858.9	58.17	0.000
Season	3	21,316.7	7105.6	481.24	0.000
Visibility Condition	3	4030.1	1343.4	90.98	0.000
Presence of Fog	1	175.7	175.7	11.9	0.001
Presence of Haze	1	37.5	37.5	2.54	0.111
Presence of Thunderstorm	1	4437.9	4437.9	300.57	0.000
Presence of Rain	1	4842.9	4842.9	328	0.000
Daylight	1	52,381.3	52,381.3	3547.61	0.000
Residuals	32,998	487,223.7	14.8	-	-
Number of Observations = 33,016					

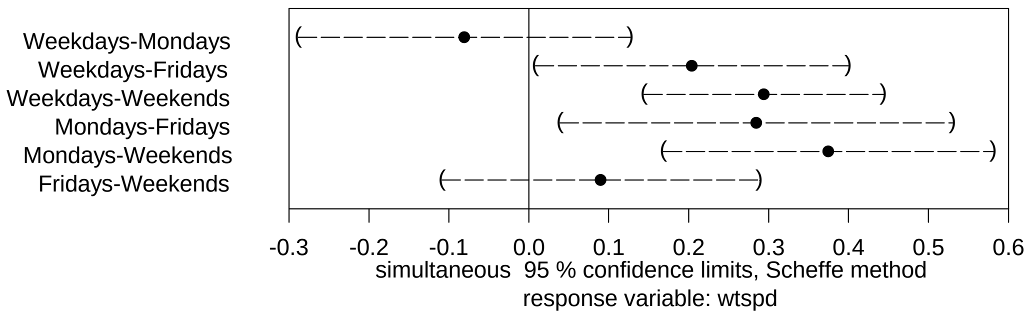
Scheffe's multiple comparison procedure was used to estimate and test factor level effects since it is a more conservative hypothesis testing (see *56*). Scheffe's test can be expressed formally as:

$$H_0 : L = 0$$
$$H_a : L \neq 0$$

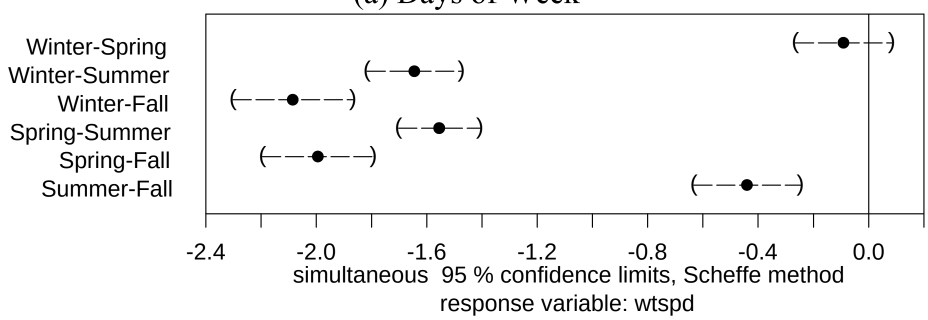
where the family of interest represents the set of all possible contrasts (L). The multiple comparison results are shown in Figure 29.

To interpret the factor level effects in Figure 29, the dotted horizontal line represents a 95 percent confidence interval (CI) of the difference between two factor levels being tested. If the CI includes zero, it implies that the difference between two factor levels is not statistically significant at $\alpha = 0.05$. For example, in Figure 29(a), factor level effects of days of week were significant at all levels except for the differences between weekdays versus Mondays and Fridays versus weekends. Similar conclusions can be drawn from the remaining figures.

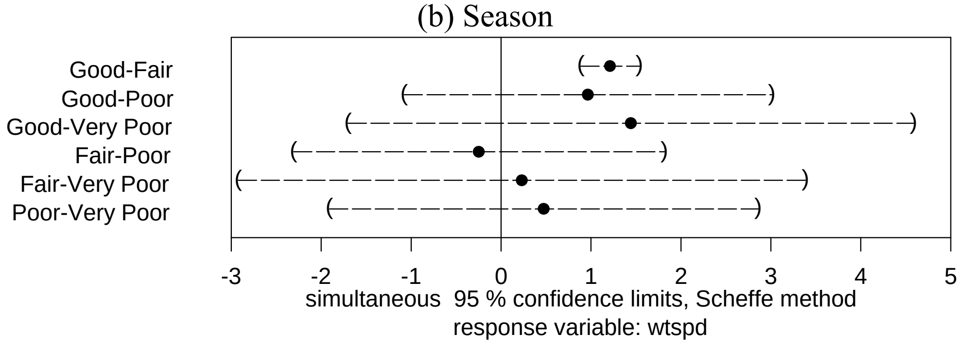
We used the results from this multiple comparison procedure to determine the appropriate set of explanatory variables in the calibration of the regression model in the next step. A linear regression with special contrast setup was used to quantify if and how much speed deviation can be attributed to each factor level.



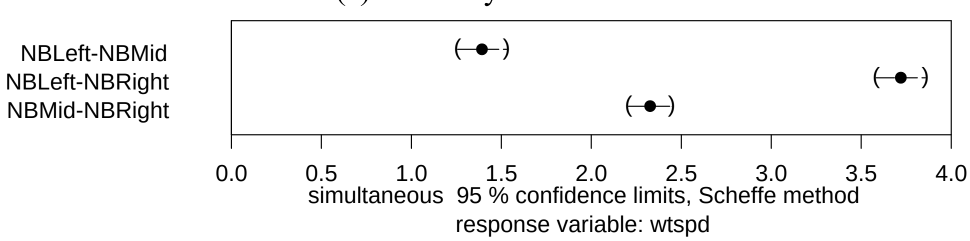
(a) Days of Week



(b) Season



(c) Visibility Condition



(d) Detector Location (Lane Effect)

Figure 29. Multiple Comparisons of Factor Levels in the Analysis of Mean Speed.

Regression Approach to ANCOVA

In the previous section, we determined the factors that can potentially affect operating speed. We can view the sample in this analysis as an unbalanced observational study where treatment sample sizes are unequal. Therefore, the regression approach to covariance analysis is needed to quantify the factor effects.

Interpretation of factor effects depends on how the contrast matrices are defined – see Venables and Ripley *(58)* for more details. In this analysis, we set up a contrast using a deviation coding scheme to separate the effect of each treatment as a deviation from the grand mean[1]. Based on the results of multiple comparisons, the following variables were re-grouped into fewer levels to simplify the regression modeling and result interpretation in the subsequent section:

- Days of week: weekdays (Monday to Thursday), Fridays, and weekends.
- Visibility condition: 3+ miles versus 3 miles or less.
- Season: summer, fall, and others (spring/winter).

In addition, regression results indicated that fog and haze conditions are not statistically significant at $\alpha = 0.05$ and therefore we excluded them from the final mean speed model.

A regression model corresponding to the covariance model in Eq. (8) can be written as:

$$\begin{aligned} v_{ijklmnp} &= v_{.......} + x_o o_{ijklmnp} + \alpha_1 I_{\alpha 1} + \alpha_2 I_{\alpha 2} + \beta_1 I_{\beta 1} + \beta_2 I_{\beta 2} + \beta_3 I_{\beta 3} + \gamma_1 I_{\gamma 1} + \gamma_2 I_{\gamma 2} + \\ &\delta_1 I_{\delta 1} + \eta_1 I_{\eta 1} + \phi_1 I_{\phi 1} + \lambda_1 I_{\lambda 1} + (\phi\lambda)_{11} I_{\phi 1} I_{\lambda 1} + \varepsilon_{ijklmnp} \end{aligned} \quad (9)$$

where,

$o_{ijklmnp} = O_{ijklmnp} - O_{.......}$;

x_o = coefficient estimate of occupancy deviation; [Author: align with rest of list.]

$I_{\alpha 1}$ = 1 if left lane, -1 if right lane, 0 if otherwise;

$I_{\alpha 2}$ = 1 if middle lane, -1 if right lane, 0 if otherwise;

$I_{\beta 1}$ = if weekdays, -1 if weekends, 0 if otherwise;

[1] In this study, we used the S-Plus statistical analysis package for our analysis. We defined a contrast setup using a deviation coding scheme to reflect our regression approach. By default, S-Plus uses the reverse Helmert contrast where each level of categorical variable is compared to the mean of the previous levels.

$I_{\beta 2}$ = 1 if Mondays, -1 if weekends, 0 if otherwise;

$I_{\beta 3}$ = 1 if Fridays, -1 if weekends, 0 if otherwise;

$I_{\gamma 1}$ = 1 if winter or spring, -1 if fall, 0 if otherwise;

$I_{\gamma 2}$ = 1 if summer, -1 if fall, 0 if otherwise;

$I_{\delta 1}$ = 1 if visibility condition is 3 miles or less, -1 if otherwise;

$I_{\eta 1}$ = 1 if thunderstorm is present, -1 if otherwise;

$I_{\phi 1}$ = 1 if rain is present, -1 if otherwise; and

$I_{\lambda 1}$ = 1 if daytime, -1 if nighttime.

The estimated coefficients of the regression model as well as their corresponding t-statistics and p-values are summarized in Table 24. The signs of estimated coefficients were found to be intuitive and in good agreement with expectation in general.

The residual plot of the estimated model against fitted values did not reveal any substantial departure from general assumptions of a normal linear regression model (see Figure 30).

In sum, the estimated speed model with respect to weather and environmental factors can be written as:

$$\begin{aligned}\hat{v} = 59.6024 - 0.7846(O_{ijklmnp} - 8.3411) + 1.7033 I_{\alpha 1} + 0.3120 I_{\alpha 2} + 0.1062 I_{\beta 1} + 0.1841 I_{\beta 2} \\ -0.0997 I_{\beta 3} - 1.2049 I_{\gamma 1} + 0.3817 I_{\gamma 2} - 0.5865 I_{\delta 1} + 1.9676 I_{\lambda 1} - 1.1373 I_{\eta 1} - 1.2402 I_{\phi 1}\end{aligned} \quad (10)$$

Deviations of Mean Speed

Table 25 summarizes the quantities of deviation from the grand mean speed under different weather and environmental conditions as well as the corresponding 95 percent confidence intervals. Confidence interval estimation requires estimated sample variance of each variable. Sample variance of the variables that were not directly derived from the regression model can be obtained using the pooled variance formula:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \ldots + (n_r - 1)s_r^2}{(n_1 - 1) + (n_2 - 1) + \ldots + (n_r - 1)} \quad (11)$$

Table 24. Linear Regression Results for Mean Speed Estimation.

Variable	Estimated Coefficient	Std. Error	t-ratio	p-Value
Constant (Grand Mean Speed)	59.6024	0.1223	487.2603	0.0000
Deviation of Occupancy (%)	-0.7846	0.0072	-109.4974	0.0000
Left Lane Indicator (1 if left lane, -1 if right lane, 0 if otherwise)	1.7033	0.0333	51.2256	0.0000
Middle Lane Indicator (1 if middle, -1 if right lane, 0 if otherwise)	0.3120	0.0296	10.5557	0.0000
Weekday Indicator (1 if weekday, -1 if weekend, 0 if otherwise)	0.1062	0.0367	2.8924	0.0038
Monday Indicator (1 if Monday, -1 if weekend, 0 if otherwise)	0.1841	0.0519	3.5455	0.0004
Friday Indicator (1 if Friday, -1 if weekend, 0 if otherwise)	-0.0997	0.0494	-2.0186	0.0435
Winter/Spring Indicator (1 if winter/spring, -1 if fall, 0 if otherwise)	-1.2049	0.0311	-38.7979	0.0000
Summer Indicator (1 if summer, -1 if fall, 0 if otherwise)	0.3817	0.0323	11.8334	0.0000
Limited Visibility Indicator (1 if visibility ≤ 3 miles, -1 if otherwise)	-0.5865	0.0556	-10.5420	0.0000
Daytime Indicator (1 if daytime, -1 if nighttime)	1.9676	0.0330	59.6558	0.0000
Thunderstorm Indicator (1 if thunderstorm present, -1 if otherwise)	-1.1373	0.1155	-9.8437	0.0000
Rain Indicator (1 if rain present, -1 if otherwise)	-1.2402	0.0646	-19.2098	0.0000
Residual standard error: 3.843 on 33,003 degrees of freedom Multiple R-Squared: 0.3994 F-statistic: 1829 on 12 and 33,003 degrees of freedom, the p-value is 0				

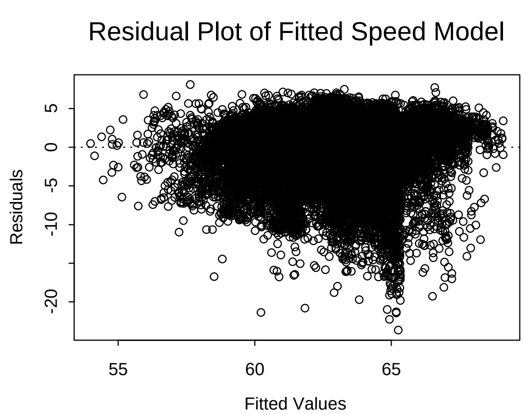


Figure 30. Residual Plot of Fitted Mean Speed Model.

Table 25. Adjustments for Mean Speed Under Different Conditions.

Factor Description	Mean Speed Adjustment (mph)	95th Percentile Confidence Interval	
		Lower Bound	Upper Bound
Grand Mean Speed • At Zero Occupancy • A Mean Occupancy (8.3411%)	66.15 59.60	- -	- -
Lane Effect • Left Lane • Middle Lane • Right Lane	1.70 0.31 -2.02	1.64 0.25 -2.08	1.77 0.37 -1.95
Day of Week Effect • Weekdays (Tu-Th) • Mondays • Fridays • Weekends	0.11 0.18 -0.10 -0.19	0.03 0.08 -0.20 -0.28	0.18 0.29 0.00 0.10
Seasonal Effects • Winter/Spring • Summer • Fall	-1.20 0.38 0.82	-1.27 0.32 0.76	-1.14 0.44 0.89
Visibility Effect • Good Visibility (3+ miles) • Limited Visibility (≤ 3 miles)	0.59 -0.59	0.48 -0.70	0.70 -0.48
Lighting Condition Effect • Daytime • Nighttime	1.97 -1.97	1.90 -2.03	2.03 -1.90
Thunderstorm Effect • Presence of Thunderstorm • No Thunderstorm	-1.14 1.14	-1.36 0.91	-0.91 1.36
Rain Effect • Presence of Rain • No Rain	-1.24 1.24	-1.37 1.11	-1.11 1.37

where,

r = number of samples,

n_i = sample size, and

s_i^2 = sample variance.

Interpretation of results in Table 25 is straightforward. For instance, rainy condition can decrease the mean speed by 1.24 mph, or the presence of a thunderstorm can reduce the mean speed by 1.14 mph. For detector location effect (lane effect), the mean speed is the highest on the left lane, followed by the middle and right lanes – the corresponding figures for deviation from the overall mean speed are 1.70, 0.31, and -2.02 mph, respectively.

It is interesting to note that the difference between regulatory daytime and nighttime freeway speed limits in Texas is 5 mph. The average speed difference contributed to daytime versus nighttime observed in this study was about 4 mph. On a positive note, this implies that the regulatory speed limit reduction at night may not be as ineffective as originally conceived. Nevertheless, the observed reduction in average traveling speed could still be attributed to several factors other than speed signing alone.

Effects on Speed-Flow Relationship

Several studies in the past concluded that speed-flow relationship can be affected by weather conditions. In this study, we examined speed-flow relationships under different combinations of weather and environmental conditions and then utilized the relationships to estimate freeway capacity based upon Greenshield's model.

Constructing Speed-Flow Relationship

The relationship between occupancy and speed is approximately linear. Because occupancy is proportionally linear to density, occupancy can be converted into density values using the following expression (*57*):

$$k = \frac{52.8}{\bar{L}_v + L_D}(O) \tag{12}$$

where,

k = density (veh/mi),

$\bar{L}_v$ = average vehicle length (ft),

L_D = length of detector (ft), and

O = percent occupancy.

To derive $\overline{L}_v$, our experience with the study location suggested the following traffic composition is appropriate: 90 percent passenger car (19 ft), 5 percent single unit truck (30 ft), and 5 percent WB-62 Interstate semitrailer (68.5 ft). This gives the weighted average vehicle length of 22.6 ft. The length of trap detectors on the Austin freeway is 22 ft. Therefore, the occupancy-to-density conversion factor is:

$$k = \frac{52.8}{22.0+16.0}(O) = 1.39(O). \tag{13}$$

We applied Greenshield's relationship for capacity estimation. The Greenshield's assumption should be fairly reasonable since the analysis was conducted using the data from the uncongested traffic flow regime.

Greenshield's speed-flow relationship can be expressed as:

$$q = vk_j\left(1 - \frac{v}{v_f}\right) \tag{14}$$

where,

q = traffic flow (vph),

v = mean speed (mph),

k_j = jammed density (veh/mi), and

v_f = free-flow speed (mph).

Solving a quadratic function in Eq. (14) gives the following speed-flow relationship:

$$v = \frac{v_f}{2} \pm \sqrt{\frac{v_f^2}{4} - \frac{v_f}{k_j}q}. \tag{15}$$

We can show that $\frac{v_f}{k_j} = \frac{v_f}{1.39O_j} = \frac{-x_o}{1.39}$. Recall that x_o is a coefficient estimate of occupancy deviation, which we calibrated earlier. Speed-flow relationship in Eq. (16) can be obtained by substituting x_o = -0.7846 into Eq. (15) and retaining only the solution that corresponds to the uncongested traffic regime.

$$v = \frac{v_f}{2} + \sqrt{\frac{v_f^2}{4} - \frac{0.7846q}{1.39}} \tag{16}$$

where v_f can be estimated from Eq. (10) for any given weather and environment conditions. The following example demonstrates the construction of speed-flow relationship using Eqs. (10) and (16).

Under normal weather condition, the speed-density function of the middle lane during daytime summer weekdays can be derived from Eq. (10) as:

$$\hat{v} = 71.8784 - 0.5645k \tag{17}$$

At free-flow condition ($k = 0$), $\hat{v} = \hat{v}_f = 71.8784$ mph. Substituting $\hat{v}_f = 71.8784$ into Eq. (16) gives the speed-flow relationship under normal condition as:

$$v = 35.94 + \sqrt{1291.63 - 0.5645q} \tag{18}$$

Speed-flow relationships under different weather conditions can be obtained in a similar manner. Figure 31 shows speed-flow relationships derived from the calibrated regression model under four different weather/environmental conditions. In the next section, we describe the procedure to estimate the theoretical capacity of freeway under different weather conditions based on the constructed speed-flow relationships.

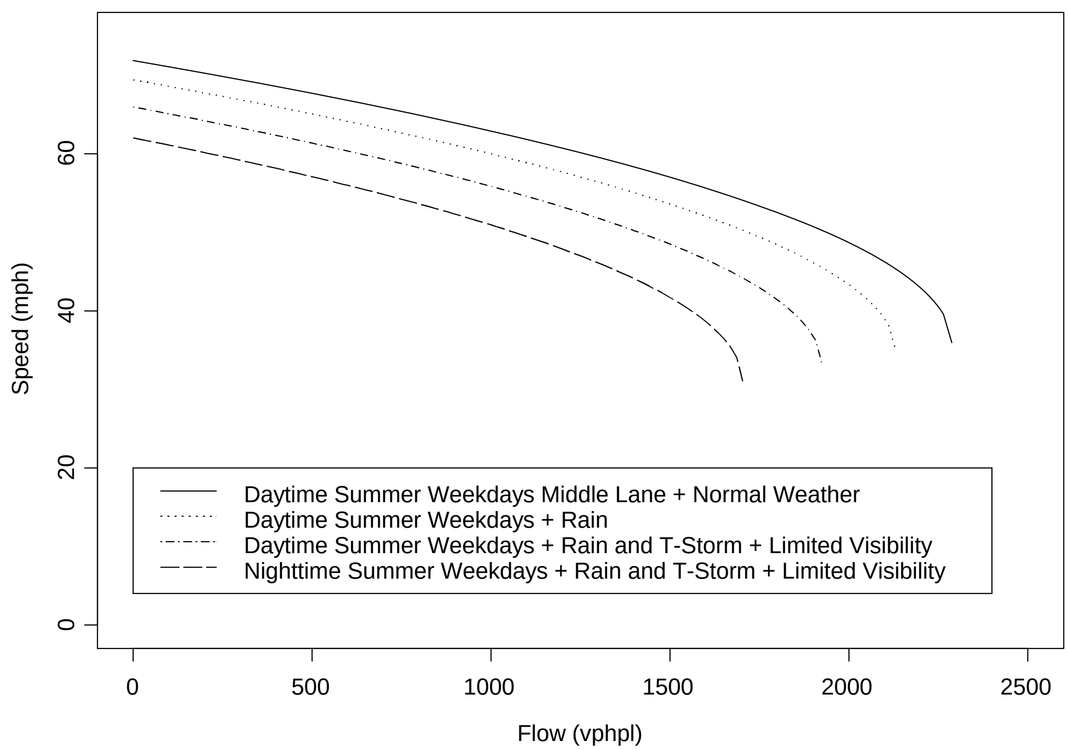


Figure 31. Speed-Flow Relationships under Different Weather Conditions.

Capacity Estimation

Theoretical capacity under Greenshield's relationship can be derived as follows:

$$q_m = \frac{v_f k_j}{4} = \frac{v_f^2}{4(0.5645)} \tag{19}$$

Free-flow speed under different weather conditions can be determined from Eq. (10). Free-flow speeds and their corresponding theoretical freeway capacities are presented in Table 26.

The results shown in Table 26 demonstrate that operating speed and freeway capacity can be reduced dramatically during adverse weather conditions. For example, the combination of rain, thunderstorm, and limited visibility can reduce the freeway capacity by approximately 16 percent during the daytime and 25 to 30 percent at night.

Table 26. Theoretical Capacity of Freeway under Different Conditions.

Conditions (middle lane)	Estimated Parameters		Capacity Reduction from Base Condition	
	Free-Flow Speed (mph)	Theoretical Capacity (vphpl)	Amount (vphpl)	Percentage (%)
Example 1:				
• Daytime Summer Weekdays + Normal Weather*	71.9	2288	-	-
• Daytime Summer Weekdays + Rain	69.4	2133	155	6.8
• Daytime Summer Weekdays + Limited Visibility	70.7	2214	74	3.2
• Daytime Summer Weekdays + Rain + T-Storm + Limited Visibility	66.0	1926	362	15.8
Example 2:				
• Nighttime Summer Weekdays + Normal Weather	67.9	2044	244	10.6
• Nighttime Summer Weekdays + Rain	65.5	1898	390	17.1
• Nighttime Summer Weekdays + Limited Visibility	66.8	1974	314	13.7
• Nighttime Summer Weekdays + Rain + T-Storm + Limited Visibility	62.0	1703	585	25.6
Example 3:				
• Nighttime Winter Fridays + Normal Weather	66.2	1938	350	15.3
• Nighttime Winter Fridays + Rain	63.7	1795	493	21.5
• Nighttime Winter Fridays + Limited Visibility	65.0	1870	418	18.3
• Nighttime Winter Fridays + Rain + T-Storm + Limited Visibility	60.2	1606	682	29.8

* Base Condition

Analysis of Speed Variation

CVS as a measure of speed variation has been reported to be a potential precursor of freeway incidents. An increase in CVS implies a presence of disturbance and/or breakdown possibility in a traffic stream, which may lead to accidents. We evaluated and quantified how level of safety changes with respect to different weather and environmental conditions using covariance analysis and regression analysis. Knowledge of unsafe traffic conditions can be used by control center operators to support the decision-making process in incident management as to when and where appropriate mitigating strategies should be deployed.

Model Development

First, we examined the scatter plots of CVS values against flow and occupancy shown in Figure 32. It should be noted that the non-linearity observed in the figure can be reasonably modeled using a quadratic functional form. Intuitively, one can expect the CVS to be higher during the free-flow condition, where vehicle speeds are nearly independent of one another, and during the congested condition, where stop-and-go traffic situations begin to occur.

Percent occupancy was selected as a covariate for the covariance model since it gives a better model's goodness-of-fit statistics, although both occupancy and flow were found to substantially reduce the error variability in the fitted models. Quadratic form of a covariate was used to incorporate the occupancy in the covariance model. It should be noted that the nearly linear occupancy-speed relationship facilitates the observation of real-time traffic data. The implication here is that, once the occupancy is known, both speed and CVS can be readily estimated using the models developed subsequently.

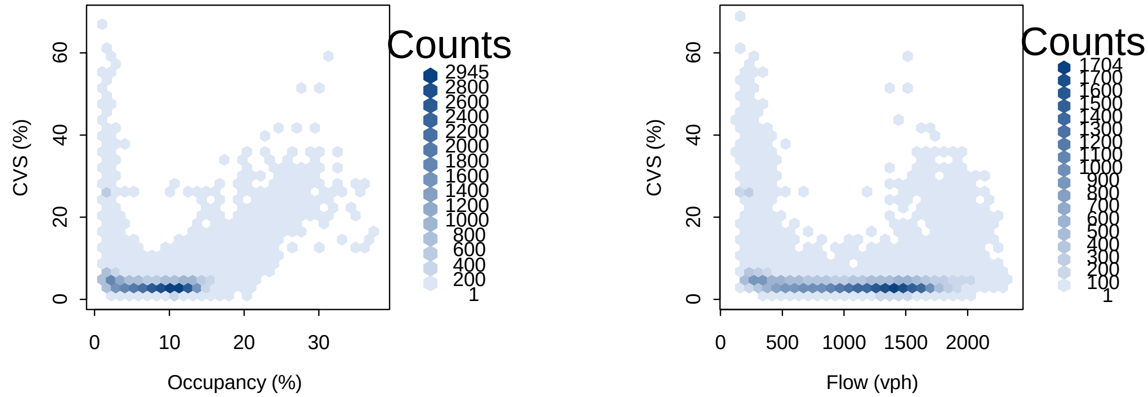


Figure 32. Scatter Plots of CVS versus Percent Occupancy and Flow.

The fitted covariance model for CVS is presented in Table 27. Weather and environmental factors that are statistically significant for CVS at α = 0.05 are similar to those of mean speed, except for fog and haze conditions.

Table 27. Covariance Analysis of Coefficient of Variation in Speed.

Factor Description	DF	Sum of Sq	Mean Sq	F Value	p-Value
15-Minute Average Occupancy	1	10,103	10,103	477.0	0.0000
$(\text{15-Minute Average Occupancy})^2$	1	255,228	255,228	12,050.1	0.0000
Detector Location	2	11,582	5791	273.4	0.0000
Day Groups	3	1409	470	22.2	0.0000
Season	3	240	80	3.8	0.0100
Visibility Condition	3	794	265	12.5	0.0000
Presence of Thunderstorm	1	524	524	24.7	0.0000
Presence of Rain	1	561	561	26.5	0.0000
Daylight	1	2677	2677	126.4	0.0000
Residuals	32,999	698,935.4	21.2	-	-
Number of Observations = 33,016					

Scheffe's multiple comparison procedure was conducted as in the case of mean speed for factors with multiple levels to determine appropriate levels in those factors. Based on the comparison results, the followings factors were categorized as follows:

- visibility: limited if 3 miles or less versus good if otherwise,
- season: spring/summer versus winter/fall, and
- days of week: weekdays versus weekends.

Table 28 presents regression results with indicator variables coded using a deviation coding scheme or deviation contrast. All the variables in the model after appropriate re-leveling of factors were statistically significant at $\alpha = 0.05$. The quadratic form of percent occupancy allows us to capture the tendency of higher CVS during both low and high occupancy conditions, which is similar to what we observed in the field data.

Table 28. Estimated Regression Model for CVS (%).

Variable	Estimated Coefficient	Std. Error	t-Ratio	P-Value
Constant	13.10505	0.1735	75.78	0.0000
Percent Occupancy	-1.7585	0.0191	-92.27	0.0000
(Percent Occupancy)^2	0.0803	0.0008	105.51	0.0000
Left Lane Indicator (1 if left lane, -1 if right lane, 0 if otherwise)	0.8243	0.0397	20.74	0.0000
Middle Lane Indicator (1 if middle lane, -1 if right lane, 0 if otherwise)	-0.6604	0.0354	-18.64	0.0000
Weekdays Indicator (1 if weekdays: Mon. through Fri., -1 if weekends)	0.2964	0.0284	10.45	0.0000
Spring/Summer Indicator (1 if spring/summer, -1 if otherwise)	0.1067	0.0276	3.87	0.0001
Limited Visibility Indicator (1 if visibility $\leq$ 3 miles, -1 if otherwise)	0.2347	0.0656	3.58	0.0003
Thunderstorm Indicator (1 if thunderstorm present, -1 if otherwise)	0.5613	0.1383	4.06	0.0000
Rain Indicator (1 if rain present; -1 if otherwise)	0.3757	0.0775	4.85	0.0000
Daytime Indicator (1 if daytime, -1 if nighttime)	0.4707	0.0420	11.21	0.0000
Residual standard error: 4.604 on 33,005 degrees of freedom Multiple R-Squared: 0.2877 F-statistic 1333 on 10 and 33,005 degrees of freedom, the p-value is 0.				

Using the calibrated regression model for CVS, the adjustments for CVS under different weather and environmental conditions can be summarized as shown in Table 29. CVS tends to be higher during poor weather conditions such as presence of rain, thunderstorm, or poor visibility. Intuitively, these conditions are known to be unsafe for motorists and the model is reflecting an increase in crash risk through an increase in CVS. It is interesting to note that the left lane (fast lane) tends to have higher CVS than others. This could be attributed to the possibility of more conflicts between speeding and normal motorists or the presence of a higher proportion of aggressive drivers in the fast lane.

Using the developed model, we established CVS profiles under different weather and environmental conditions. The CVS profile can be used to identify desirable traveling conditions under a range of occupancy levels. We refer to this concept as the *safety comfort zone*, which is discussed in the next section.

Safety Comfort Zone

For any given weather and environmental conditions, a CVS-occupancy diagram can be constructed using the calibrated model as shown in Figure 33. Now, control center operators can use this profile to determine when and at what occupancy the CVS tends to be higher. Using a percentile-based approach, assume that an operator wants to maintain the CVS below the 90th percentile of all the observed CVS values. This condition implies that CVS should not exceed the critical threshold more than 10 percent of the time. Based on the historical CVS data, the 90th percentile of CVS is approximately equal to 6 percent, which is represented as the horizontal broken line in Figure 33. In practice, this critical CVS value should be specified by TMC personnel based upon historical data and field experience.

Let us define the traffic condition below this critical CVS line as a *safety comfort zone* – a condition where the risk of collision is not excessive. Therefore, from this figure, we can observe that the safety comfort zones become smaller as the weather conditions deteriorate, such as presence of rain or limited visibility condition.

Table 29. Adjustments for CVS under Different Conditions.

Factor Description	Mean Speed Adjustment (mph)	95th Percentile Confidence Interval	
		Lower Bound	Upper Bound
Grand Mean Speed			
• At Zero Occupancy	13.15	-	-
• A Mean Occupancy (8.3411%)	4.07	-	-
Lane Effect			
• Left Lane	0.82	1.64	1.77
• Middle Lane	-0.66	0.25	0.37
• Right Lane	-0.16	-2.08	-1.95
Day of Week Effect			
• Weekdays (Mon. – Fri.)	0.30	0.24	0.35
• Weekends	-0.30	-0.35	-0.24
Seasonal Effects			
• Spring/Summer	0.11	0.05	0.16
• Fall/Winter	-0.11	-0.16	-0.05
Visibility Effect			
• Good Visibility (3+ miles)	-0.23	-0.36	0.70
• Limited Visibility (≤ 3 miles)	0.23	0.11	-0.11
Lighting Condition Effect			
• Daytime	0.47	0.39	0.55
• Nighttime	-0.47	-0.55	-0.39
Thunderstorm Effect			
• Presence of Thunderstorm	0.56	0.29	0.83
• No Thunderstorm	-0.56	-0.83	-0.29
Rain Effect			
• Presence of Rain	0.38	0.22	0.53
• No Rain	-0.38	-0.53	-0.22

Another potential application of CVS profile is that it can be used to assist control center operators in determining when the DMS should be activated and deactivated. For instance, DMS could be activated during the high CVS value in order to reduce potential conflicts and then deactivated when the traffic situation returns to the safety comfort zone. The exact contents of DMS are beyond the scope of this study.

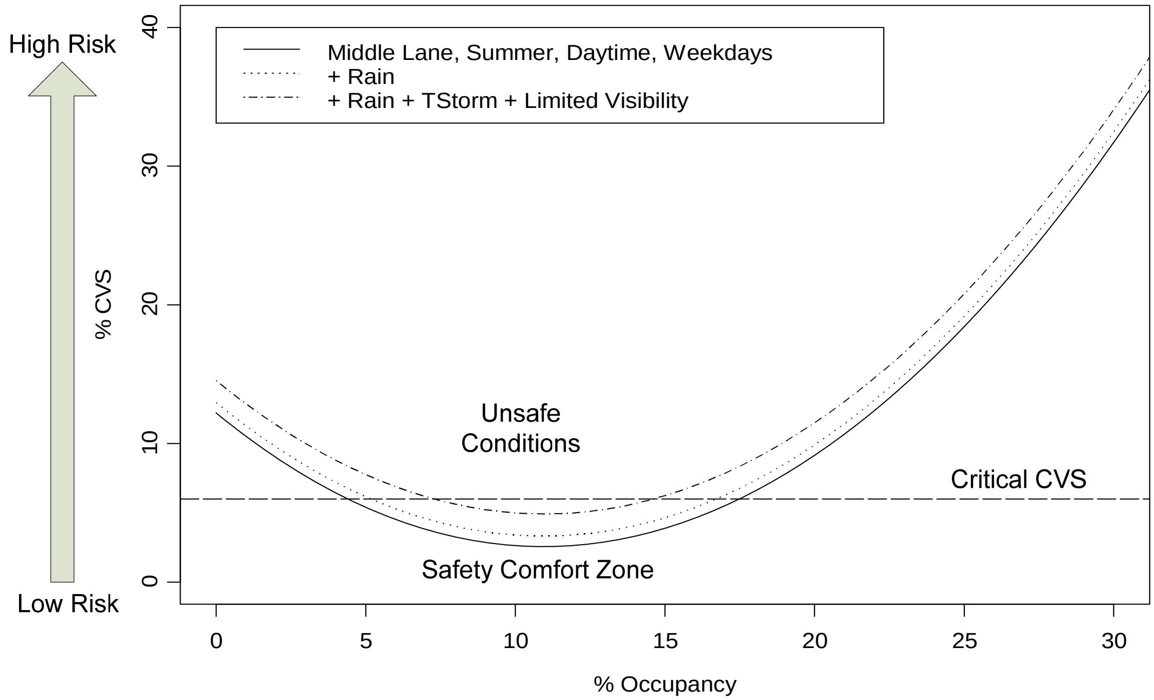


Figure 33. CVS Profiles under Different Conditions.

SUMMARY

In this study, we examined the weather and environmental impacts from both operational and safety viewpoints. On the operation side, we assessed if and how mean operating speed, speed-flow relationship, and freeway capacity are affected by different weather and environmental conditions. On the safety side, we examined the changes in speed variation as measured by CVS, which has been found to be a potential precursor of freeway incidents in many recent studies. Covariance analysis was used to conduct preliminary factor screening while reducing the error variability in the model through the use of covariates or concomitant variables. Then, a Scheffe multiple comparison procedure was performed to determine appropriate leveling in each factor. Finally, a regression approach with deviation contrast coding scheme was used to quantify the deviations from the overall mean of the interested values – which are mean speed and CVS in this study. A concept of safety comfort zone was proposed to assist control center operators in identifying traffic and weather conditions where there exists excessive risk of accidents.

We found that adverse weather conditions such as rain and thunderstorm can approximately reduce the mean traveling speed by 5 percent and the capacity by 16 to 30 percent depending on concurrent traffic and environmental conditions. The adverse weather conditions were also found to increase the potential of incidents on freeways, particularly during low-flow and congested conditions. For instance, CVS values could be at least 25 percent higher than average during the presence of rain and thunderstorm. CVS profiles and a concept of safety comfort zone developed in this study can be used to prompt and/or support the decision of control center operators to deploy appropriate freeway management strategies in order to increase freeway throughput as well as minimize the risk of accidents.

The analysis approach conducted in this study can be expanded to include multiple locations in the future. In addition, the impacts of weather and environmental conditions on traffic operations during congestion are yet to be examined. Knowledge of operational impacts of different weather conditions can be incorporated into microscopic simulation models in order to analyze for effective freeway management strategies. The research results presented herein provide a much needed insight into operational and safety impacts of weather and environmental conditions, which can be used to support the implementation of an effective freeway incident management program.

CONCEPT OF OPERATIONS FOR MANAGING FREEWAY OPERATIONS DURING WEATHER EVENTS

One of the primary objectives of this research project was to develop a generic concept of operations for how TxDOT TMC operators should respond to and manage traffic during weather events. This section provides generic concepts of operations for many of the weather events that are typical in Texas. We developed these generic responses with the idea that TxDOT operators could use these as an initial starting point to develop more detailed concepts of operations that are specific to their individual districts.

Because different districts are likely to have different levels of deployments of systems for monitoring weather, we struggled with finding an initial trigger event that would be common across all districts. To this end, we decided to develop our generic concepts of operations based on National Weather Service alerts since we believe that every district does or can relatively easily gain access to this information. The following section provides a brief overview of the National Weather Service alert system. Following that section, we process our concepts of operations for various weather events.

NATIONAL WEATHER SERVICE LEXICON FOR WEATHER ALERTS

The National Weather Service is responsible for "weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy" *(59)*. The NWS accomplishes the above mission with a network of national, regional, and local weather centers. The NWS utilizes numerous products to convey the current weather information. Traditionally, this information has been issued via radio and television broadcasts. However, with the increasing popularity of the Internet, other means of disseminating information have been employed. Figure 34 shows a NWS product that lists the comprehensive status information for the United States. Picking the dropdown menu and selecting a state produces a text listing of all the information currently being provided.

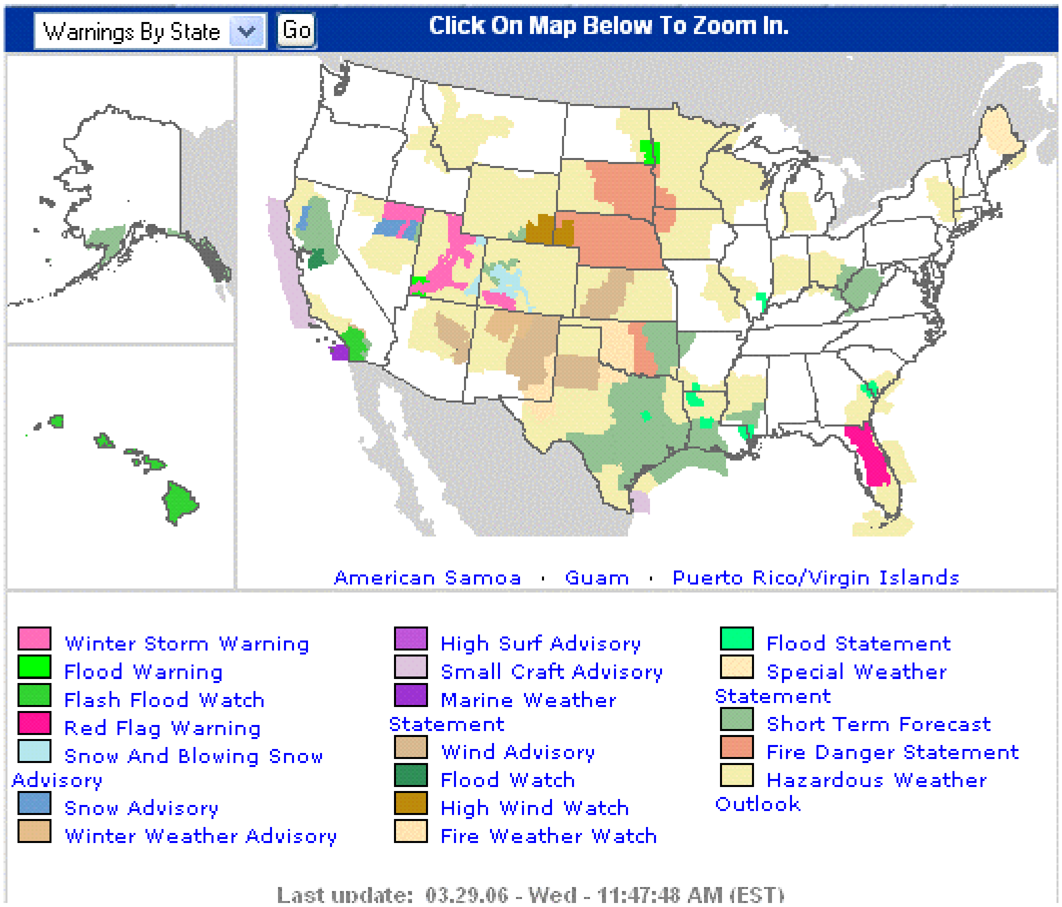


Figure 34. National Weather Service – Warnings by State *(60)*.

At the heart of all of the information distributed by the NWS is a formalized lexicon of weather status. Table 30 lists and defines the terminology employed by the NWS. Of particular note is the fact that there are time frames associated with the different types of notifications. There are also different notifications based on the severity of the weather event. Figure 35 illustrates the terms in the lexicon and when each type of notification is used depending on the time frame and severity of the event.

Table 31 identifies a number of the most common notifications issued by the NWS and the criteria for when the notification is issued.

Table 30. National Weather Service Lexicon (62).

Term	Definition	Applies to:	Timeframe
Outlook	A hazardous weather or hydrologic event may occur in the next several days.	All types of weather	Up to 7 days prior to start of event.
Watch	Significant increased risk of hazardous weather or hydrologic events.	All types of weather	6 hours prior to potential start of event (typical).
Warning	Hazardous weather or hydrologic event is imminent or occurring. Threat to life or property is present and protection actions may be necessary.	All types of weather	Start of event (typical).
Advisory	Hazardous weather or hydrologic event is imminent or occurring. An advisory is for less serious conditions than warnings. Caution should be exercised.	All types of weather	Start of event (typical).
Statement	An update mechanism for watches and warnings, containing the latest information.	All types of weather	Periodically through the event, until conclusion.
Forecast	Specific and detailed weather information and predictions on a county by county basis	All types of weather	Forecast projections are in effect for 1 to 6 hours and can be issued anytime.

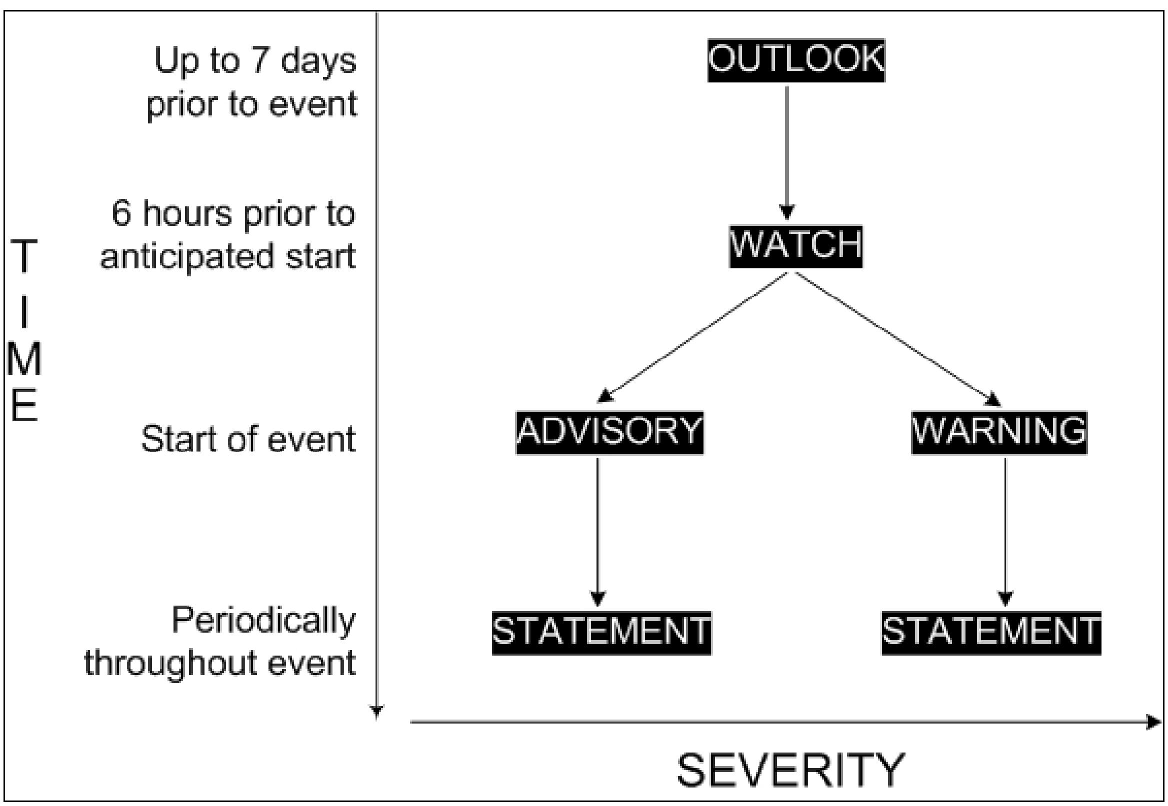


Figure 35. Illustration of NWS Lexicon.

Table 31. Common National Weather Service Notifications (61,62).

Event/Condition	Type of Notification	Criteria
Blowing/Drifting Snow	Advisory	Intermittent visibility less than ¼ mile.
Freezing Rain/Freezing Drizzle	Advisory	Expected accumulations less than ¼ inch.
Sleet	Advisory	Expected accumulations less than ½ inch.
Snow	Advisory	Expected accumulations between 1 and 4 inches in a 12-hr period.
Lake Effect Snow	Advisory	Expected accumulations between 3 and 5 inches in a 12-hr period.
Winter Weather	Advisory	Mixture of precipitation (snow, freezing rain, drizzle, sleet, blowing snow) is expected but will not reach warning levels.
Wind Chill	Advisory	Criteria varies by region of country.
Frost	Advisory	Used for widespread frost during growing season.
Dense Fog	Advisory	Dense fog covers widespread area and visibility if frequently reduced to ¼ mile or less.
Wind	Advisory	Wind gusts between 40 and 57 mph for any duration of time.
	High Wind Warning	Sustained winds of 40 mph or greater are expected to last for 1 hour or more. Also used for non-thunderstorm related winds of more than 58 mph for any time period.
Urban and Small Stream Flood	Advisory	Used to alert public to flooding that is an inconvenience and does not pose threats to life or property.
Heat	Advisory	Used to alert public to daytime temperature heat indices of 105 ºF or greater and nighttime heat indices of 80 ºF or greater for two or more consecutive days.
	Excessive Heat Warning	Used to alert public to daytime temperature heat indices of 115 ºF or greater for 3 hours or longer.
Health	Advisory	Used to alert public when ground level ozone readings are expected to reach moderate levels.
Tornado	Watch	Conditions favorable for development of tornados over the next 6 hours.
	Warning	Tornado was sighted or indicated by radar. Message will include location and path.

Table 31. Common National Weather Service Notifications (Cont.).

Event/Condition	Type of Notification	Criteria
Severe Thunderstorm	Watch	Conditions favorable for development of severe thunderstorms over the next 6 hours.
	Warning	Used for thunderstorms producing ¾ inch or larger hail and/or winds in excess of 58 mph. Message will include location of storm, path, and the threat from the storm.
Flash Flood	Watch	Flash flooding is possible.
	Warning	Rapid flooding is either already occurring or imminent.
Freeze	Warning	Issued during growing season when temperatures are expected to drop below 32 ºF for a significant amount of time.
Wind Chill	Warning	Used to alert public when temperatures are expected to reach –10 ºF or colder with a minimum wind speed of 10 mph.
Tropical Storm	Watch	An announcement used for coastal areas that could experience tropical storm conditions within the next 36 hours.
	Warning	Used to alert public when sustained winds of 39 to 73 mph associated with a tropical cyclone are expected within 24 hours or less. Warning affects a specific coastal area.
Hurricane	Watch	An announcement used for coastal areas that could experience hurricane conditions within the next 36 hours.
	Warning	Used to alert public when sustained winds of 74 mph or greater associated with a hurricane are expected within 24 hours or less. Warning affects a specific coastal area.
Winter Storm	Watch	Conditions are favorable for hazardous winter weather conditions, which could include heavy snow, blizzards, or significant accumulations of freezing rain or sleet. Winter storm watches are typically issued 12 to 36 hours prior to the event.
	Warning	Hazardous winter weather conditions are occurring or are imminent. A winter storm warning will be issued for a combination of two or more of the following events: heavy snow, freezing rain, sleet, strong winds. Individual warnings are issued if only one condition is present.
Flood	Warning	A warning issued to specific communities or areas along a river when flooding is occurring or imminent. Information usually includes specific crest (high of water) information.

LIMITED VISIBILITY

A concept of operations for limited visibility conditions is summarized in Table 32. Though developed for fog conditions, the concept of operations can be applied not only to limited visibility conditions created by fog, but also to limited visibility conditions created by blowing sand, smoke, or heavy rainfall.

Table 32. Concept of Operations for TMC Response to a Limited Visibility Event.

Trigger	Actions
NWS Outlook/ Forecast	• Review operational status of RWIS stations • Review communication status to DMS and HAR locations • Review established visibility criteria • Review preprogrammed limited visibility messages in DMS/HAR devices • Review contact information of emergency response personnel/dispatchers • Review preposition location for service/courtesy patrols
NWS "Dense Fog Advisory"	• Monitor air temperature, dew point, and wind speed measures for RWIS • Monitor video surveillance system • Monitor average speed measures from traffic detection system • Alert dispatchers to preposition service/courtesy patrol
Limited Visibility Conditions • Detected OR • Reported	• Verify limited visibility condition location using video surveillance system • Compare visibility to established thresholds • Implement Limited Visibility *ACTS* to accomplish the following: o Reduce travel speed to correspond to stopping sign distance provided by visibility conditions o Increase following distance separation between vehicles o Encourage automobile and truck traffic to use separate lanes o Prevent additional vehicles from entering affected area • Report specific limited visibility location to emergency service providers
Limited Visibility Conditions Begin to Dissipate	• Monitor air temperature, dew point, and wind speed measures for RWIS • Monitor video surveillance system • Adjust responses as appropriate for conditions
Limited Visibility Conditions Completely Dissipates	• Return to normal operating status

The initial trigger event for the limited visibility response is when the NWS issues a short-term forecast (or outlook) indicating that conditions are favorable for fog to occur. Fog occurs when the following atmospheric conditions exist: the ambient air temperature is equal to the dew point and wind speeds are extremely light. While fog can form anytime in Texas, limited visibility situations due to fog occur in the early to mid-morning hours or in the early evening hours a couple of hours after sunset. Generally, this forecast occurs 2 to 6 hours in advance of the actual event. When the forecast is for weather conditions that are favorable for the formation of fog, the operator should take the following actions:

- *Review operating status of the installed road weather information systems to ensure equipment is functioning properly.* The operator should compare the air temperature, dew point, wind speed, and visibility sensors from each station to a calibration site to ensure the equipment is functioning properly. The operator may also want to review internal maintenance logs, work order logs, and/or trouble reports for information on status of equipment or sensors that are malfunctioning or inoperable.
- *Review established visibility thresholds that trigger different operator responses*. The operator should also review the visibility thresholds that trigger different types of response (e.g., speed advisory messages based on the amount of available sight distance), if established.
- *Review visibility "landmarks."* Using the video surveillance system, the operator should review visibility landmarks at fog-prone locations. The landmarks could be a building, culverts, sign supports, etc., that are a fixed distance in the field of view of the camera. At some locations, TxDOT may wish to install placards bearing visibility legends at known distances in the view of the video surveillance system to assist the operator in assessing the amount of visibility available at a site.
- *Review operational status of DMSs/HARs in potential fog area.* The operator should also review the operational status of all DMSs/HARs and other motorist notification systems that could be used to alert travelers of poor visibility conditions. The operator should report all malfunctioning or inoperable equipment to the appropriate maintenance personnel, if it has not already been done.
- *Review contact information for emergency response personnel/dispatchers.* The operator should also review the contact information for appropriate emergency response personnel (including fire, police, sheriff, courtesy patrols, wrecker services, etc.) in fog-prone areas. The operator should verify that contact information is accurate. If the event is expected to occur during non-work times, the operator should verify on-call personnel.
- *Identify/review preposition location for service and courtesy patrols.* In those locations where service or courtesy patrols are available, TxDOT may wish to

identify safe locations where service or courtesy patrol can move or store disabled vehicles outside of the travel lanes. The operator should review where the storage areas are located as well as familiarize him- or herself with how to access these sites.

- *Monitor air temperature, dew point, and wind speed measurements from RWIS sites*. After reviewing all equipment and response procedures and protocols, the operator should begin the process of monitoring the air temperature, dew point, and wind speed measurements from available RWIS sites. The operator is looking for locations where the air speed and dew point are approximately equal with little to no wind speed. If the RWIS site also has a visibility sensor, the operator should monitor those readings as well.

The NWS issues a "dense fog advisory." A dense fog advisory generally indicates the dense fog covers a *widespread* area and visibility is *frequently reduced* to less than ¼ mile (1320 ft) or less. Receipt of a dense fog advisory does not necessarily indicate that hazardous driving conditions exist or that an operator response is required. Upon receipt of a dense fog advisory, the operator should take the following actions:

- *Increase monitoring air temperature, dew point, and wind speeds from RWIS sites (if available).* As conditions begin to worsen, the operator should place more emphasis on reviewing RWIS information, particularly if the site is equipped with visibility sensors or located in a fog-prone area.
- *Increase monitoring of video surveillance systems*. The operator should also use the video surveillance system to visually detect areas of potential limited visibility.
- *Monitor average speed measures from detection system*. The operator can also monitor the average speed measures from roadway detection stations to identify locations of usual speed reductions. Lower than typical average speeds can be an indication that limited visibility conditions exist in an area.
- *Alert dispatchers to preposition service/courtesy patrols.* If the district has identified locations for preposition service/courtesy patrols to aid in the rapid removal of stalled vehicles, the operator should alert their dispatcher that limited visibility conditions are developing and that the patrol should take their assigned position. The courtesy

patrols can also potentially provide operators with estimates of available visibility from their predefined positions.

When the operator either: 1) detects an area where fog is beginning to form, or 2) is notified that fog is forming at a particular location, the operator should then *assess the amount of visibility restriction*. Using the video surveillance system, the operator should: 1) visually verify that fog is forming in the area, and then 2) determine the amount of visibility reduction using either information from the RWIS or from the visibility landmarks. The operator should compare visibility conditions to visibility response thresholds established by the district to determine the appropriate response.

As long as the available visibility exceeds the required stopping sight distance at a particular speed, then the operator does not need to take action. However, when the available visibility is less than the stopping sight distance, the operator should advise drivers to travel at the appropriate speed needed to provide the required stopping sight distance. The traffic management objective is to ensure that drivers are maintaining a uniform speed that provides them with adequate stopping sight distance. An appropriate operator response would be to issue speed advisories on DMSs and other information dissemination devices advising drivers of the appropriate speeds for the measured visibility conditions. Table 33 provides the suggested criteria for issuing speed advisories for different visibility requirements. These speed advisories provide sufficient stopping sight distance for the given visibility distance. These speed advisories are based upon level terrain, a 2-second perception and reaction time, and a braking deceleration rate of 11.2 ft/s^2.

Table 33. Suggested Criteria for Issuing Speed Advisories for Available Visibility Conditions.

Visibility Distance (x) ft.	Recommended Advisory Travel Speed (mph)
x ≥ 1100 ft	No Advisory Needed
1100 ft > x ≥ 800 ft	70 mph
800 ft > x ≥ 500 ft	55 mph
500 ft > x ≥ 300 ft	40 mph
300 ft > x ≥ 150 ft	25 mph
x < 150 ft	Prohibit travel/close freeway

If the visibility distance cannot be measured or estimated accurately, then the operator can provide other types of advisories such as "USE CAUTION" or "REDUCE SPEED" messages as appropriate.

As the visibility conditions continue to approach zero, the natural tendency of drivers is to pull of to the sides of the roadway and stop their vehicles. When they do this, they often leave their headlights and brake lights illuminated. Previous research suggests that when they do, other approaching motorists are drawn to their taillights, thereby increasing the potential for being struck from the rear by oncoming traffic. Therefore, during conditions when sight distance and visibility are severely limited, the operator's management objective should change from one of maintaining uniform travel speeds appropriate to provide safe stopping sight distance to limiting the potential for vehicles to run into the back of stopped vehicles. For those vehicles inside the limited visibility area, the operator should consider implementing management strategies that reduce the potential of oncoming vehicles colliding with stopped or slower moving vehicles. Examples of the types of management strategies that an operator could implement in these conditions include the following:

- Deploy messages on DMSs and HARs alerting travelers to the presence of vehicles that have stopped or the end of queued vehicles.
- Use vehicle lane restrictions that separate large trucks from passenger vehicles in the traffic stream.
- Close ramps and other access points to the freeway to prevent vehicles from entering the freeway.
- Detour traffic from the freeway to a rest area or other appropriate location where traffic can be stored.

In low volume conditions or at isolated areas, TxDOT may wish to establish pilot car operations through the fog area using courtesy patrols, maintenance vehicles, or law enforcement vehicles. Vehicles would have to queue in areas where visibility remains relatively good.

For those travelers outside the limited visibility area, the operator's management objective is to prevent vehicles from entering the limited visibility area. To accomplish this goal, the operator should implement management strategies designed to keep vehicles from entering the limited visibility area. For example, the operator may wish to use the appropriate DMSs and other devices to establish detour routes around the limited visibility area. The operator should also alert the media to known locations of limited visibility and request that travelers use alternate routes or delay taking their trips until conditions have improved. Areas of limited visibility should also be highlighted on the district's Internet traffic conditions displays.

PONDING/FLASH FLOOD EVENTS

Ponding and flash floods are generally associated with major rain storms that dump a significant amount of water in a relatively short period of time (i.e., a high intensity rain event). Ponding occurs when water cannot drain off a roadway as quickly as it falls. It is generally caused by insufficient or ineffective drainage, insufficient slope to adequately drain the water, or settle of the pavement structure itself. Flash flooding generally occurs when runoff from the event rises over into the roadway facility. Regardless of how the water enters the roadway, ponding and flash floods represent a major problem for TMC operators.

Table 34 shows the generic concept of operations for ponding and flash flooding events. Note that the first triggering event might be an NWS "Flash Flood Watch" or "Severe Thunderstorm Watch" alert. This implies that conditions are right for these types of events to occur – it does not mean that ponding and flash flooding are currently occurring. These types of alerts generally serve to alert the operator to be prepared to respond to a ponding or flash flood event. Upon receiving these initial alerts, the general response of the operator is to check the operational status of the field monitoring and communication devices, and review the established response procedures and criteria. The operator should also review contact information associated with appropriate emergency and maintenance responders.

The next trigger event is when the NWS issues a "Flash Flood Warning" or "Severe Thunderstorm Warning." NWS issues these types of alerts when the event is actually occurring. When an operator receives one of these alerts, the general response is to begin monitoring known problem locations with whatever technology is available. This may include monitoring rain gauge and stream gauge sensors to determine if the rate of rainfall exceeds established criteria, monitoring low water crossing and common flood points using video surveillance camera, or monitoring in-pavement traffic sensors to determine if ponding water is causing severe reductions in travel speeds.

Table 34. Concept of Operations for TMC Response to a Ponding/Flash Flood Event.

Trigger	Actions
• NWS "Flash Flood Watch" Alert or NWS "Severe Thunderstorm Watch" Alert	• Review operational status of RWIS stations • Review communication status to DMS and HAR locations • Review established ponding/water depth criteria • Review preprogrammed ponding/flash flooding messages in DMS/HAR devices • Review contact information of emergency response and maintenance personnel/ dispatchers • Review preposition location for service/courtesy patrols
• NWS "Flash Flood Warning" Alert or • High Intensity Rainfall Detected	• Monitor rainfall rate and intensity measures from RWIS • Monitor video surveillance system • Monitor average speed measures from traffic detection system • Alert dispatchers to preposition service/courtesy patrol
Ponding/Flash Flooding • Detected or • Reported	• Verify ponding/flash flooding location using video surveillance system • Determine/estimate depth of ponding in travel lanes and if travel lane(s) is(are) passable or impassible • Compare water depth to established thresholds • Implement Ponding/Flash Flooding Event *ACTS* to accomplish the following: o Prohibit vehicles from entering ponding/flash flood area o Promote smooth transition of traffic to open lanes o Encourage automobile and truck traffic to use separate lanes o Prevent additional vehicles from entering affected area • Report specific flooding locations to emergency service providers • Implement alternative route plan for large-scale roadway flooding • Continue monitoring video surveillance and adjust response as appropriate
Ponding/Flash Flooding Begins to Dissipate	• Adjust responses as appropriate for conditions • Notify emergency responders that ponding/flash flooding is subsiding
Ponding/Flash Flooding Completely Dissipates	• Return to normal operating status

A number of factors (such as drainage, rainfall intensity rates, number of lanes, presence of shoulders, etc.) affect how quickly water will pond on a roadway. As a general guideline, the operator should consider issuing speed advisories when at least half of the inside lane is covered with water. This would mean that the outside wheel path would have approximately 1½ inches of water in the wheel path. We believe that depth of water is sufficient to cause drivers to reduce their speeds. The reason for issuing the speed advisory is to alert traffic upstream of where the water is encroaching to be aware of slow moving vehicles. When the ponding is sufficient to cause water to stand in both wheel paths, we recommend that TxDOT operators consider implementing lane closure procedures upstream of the event to ensure the smooth transition of traffic to the open lanes. If the water depth gets to the point that the roadway is no longer passable, TxDOT operators should implement strategies that encourage motorists to divert to other facilities. Figure 36 and Figure 37 are illustrations of these proposed criteria.

For lower speed roadways (such as frontage roads), the TxDOT Houston District has developed the following response criteria:

- 6 inches on roadway, alert law enforcement of potential flooding problem;
- 9 inches of standing water on the roadway and still raining, flash flooding is probably imminent; and
- 12 inches of standing water on the roadway and still raining, TxDOT operators should close the road for safety reasons. If it stops raining or is slowing down, the TxDOT operator may elect not to close the road.

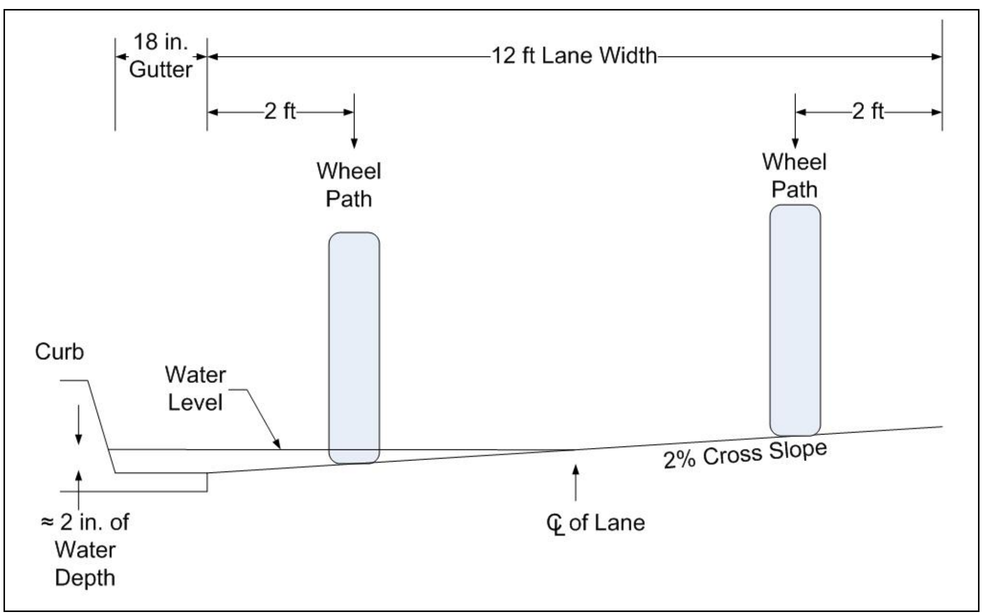


Figure 36. Illustration of Criteria for Issuing Speed Advisories for Ponding in Roadway.

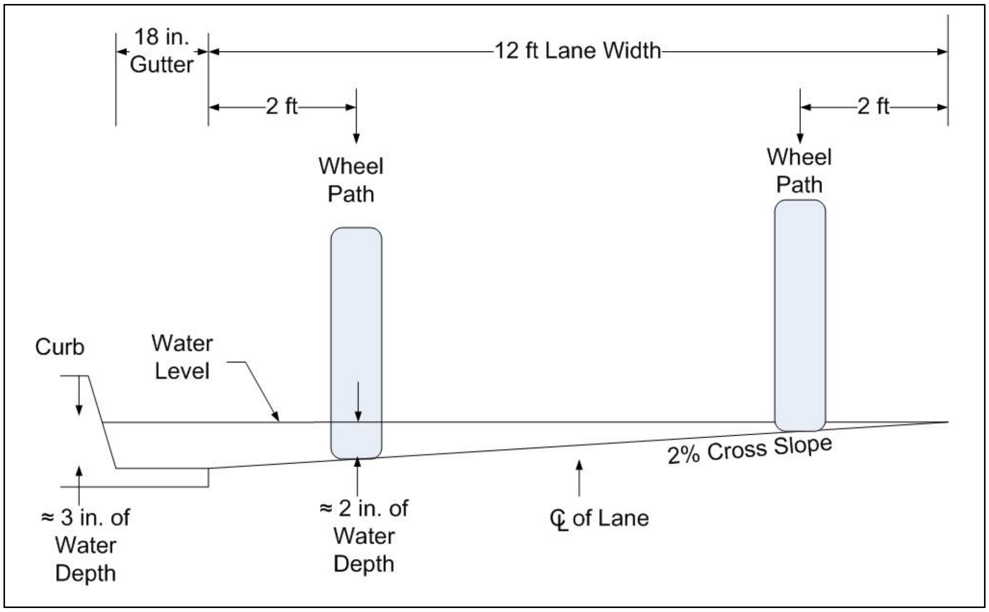


Figure 37. Illustration of Criteria for Issuing Lane Closures for Ponding in Roadway.

HIGH WINDS

High wind is another significant weather event for which TxDOT operators may wish to implement traffic management strategies. High winds may be a sole phenomenon (i.e., occurring not in conjunction with another event) or may be associated with another weather event. For example, high winds are possible with heavy thunderstorm or winter storm events. Operators may also be concerned about issuing high-wind advisories during tropical storm/hurricane events where wind is the primary impact and the roadway is still open to vehicles.

This issue with high winds is not only the speed but the direction from which the wind is blowing. As shown in Figure 38, agencies need to most be concerned when the main force of the wind is blowing perpendicular to the cross street traffic. Strong crosswinds can overturn vehicles. High-profile vehicles (such as trucks and recreational vehicles) are particularly susceptible to overturning in crosswinds.

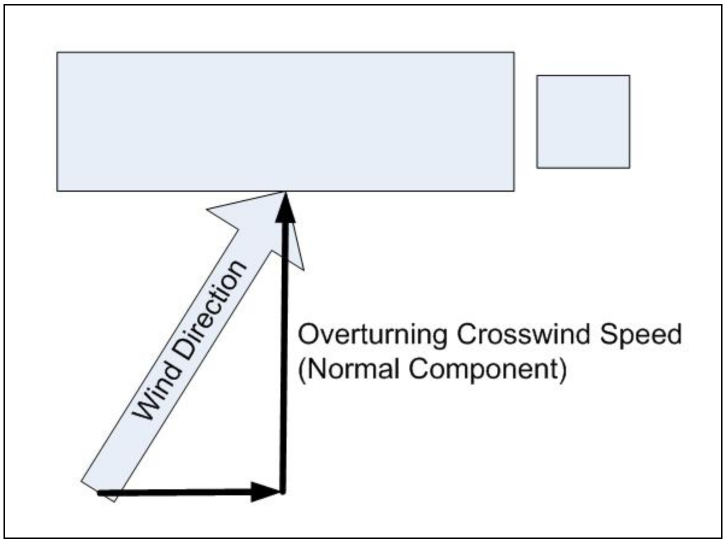


Figure 38. Overturning Crosswind Speed as the Normal Vector Component of Wind Speed.

Table 35 shows the concept of operations that we developed for responding to high-wind events. As mentioned above, high winds can be a weather phenomenon by itself or could be associated with other types of weather events, such as severe thunderstorms, winter storms, tropical storms, and hurricanes. When the operator receives any NWS alerts associated with these types of events, he or she should be prepared to implement a high-wind alert; however, action is not required until conditions measured in the field become severe. If wind detection technology is available, the operator should monitor these devices to determine speed and direction of the wind. Generally, these devices have been installed at critical locations where crosswinds occur with regular frequency, such as on tall bridges or severe roadway cuts that tend to create a wind tunnel effect.

Before implementing a traffic management strategy at a particular location, the operator needs to know the magnitude of the crosswind speed. The TTI Houston Office has developed a tool – called the Wind Warning Calculator – that calculates the crosswind speed vector for particular trouble locations in the TxDOT Houston District (*16*). Figure 5 shows a screen capture of the calculator. The Wind Warning Calculator is based on wind tunnel research performed in England to determine the crosswind speed required to overturn various configurations of high-profile vehicles (*17*). The results of this research are shown in Figure 6, while Figure 7 illustrates the types of trucks examined in this research.

Table 35. Concept of Operations for TMC Response to a High Wind Event.

Trigger	Actions
• NWS "Wind Watch" Alert or • NWS "Severe Thunderstorm Watch" Alert or • NWS "Winter Storm Watch" Alert	• Review operational status of RWIS stations • Review communication status to DMS and HAR locations • Review established high-wind advisory speed information • Review preprogrammed high-wind warning messages in DMS/HAR devices • Review contact information of emergency response and maintenance personnel/dispatchers • Review established route plans for detouring high-profile vehicles during high wind events • Review available areas for staging/storing high-profile vehicles until weather event passes. • Verify contact information of heavy-duty wrecker services
• NWS "High Wind Warning" Alert or • High Winds Detected	• Monitor average and wind speed gusts from RWIS • Monitor video surveillance system • If heavy-duty wreck contract exists, notify dispatchers of potential location of high wind • Place maintenance forces on alert to potential for high-wind closure and removal of debris from high-wind event
High Winds • Detected or • Reported	• Verify high-wind conditions exist at location using video surveillance system • Compute wind speed vector normal to direction of travel (crosswind speed) • Compare computed wind speed normal vector to established thresholds • Implement High-Wind Event *ACTS* to accomplish the following: o Advise drivers of high-profile vehicles of appropriate travel speed for high-wind conditions o Restrict high-profile vehicles that could potentially overturn in high-wind event from facility or roadway and provide adequate detouring for these vehicles o Encourage automobile and truck traffic to use separate lanes • Report specific locations of high-wind restrictions to enforcement personnel • Notify emergency service providers to specific locations of high-wind warnings • Implement alternative route plan for detouring high-profile vehicles • Notify maintenance forces to repair damage and/or remove debris caused by high winds • Continue monitoring video surveillance and adjust response as appropriate
High Winds Begin to Dissipate	• Adjust responses as appropriate for conditions • Notify emergency responders that high-wind condition is subsiding
High Winds Completely Dissipate	• Return to normal operating status

To use the Wind Warning Calculator, the operator needs to either select the desired location where wind advisories are likely to be posted or enter the azimuth of the direction of travel on the roadway. After selecting or entering the location description, the operator needs to enter the speed and the direction (in degrees) of the wind. The calculator then computes the crosswind speed, compares the computed value to the overturning crosswind speed shown in Figure 5, and recommends the appropriate response – either posting a speed warning advisory or closing the roadway based on the prevailing conditions.

SEVERE THUNDERSTORM

Severe thunderstorms are a common weather event in all parts of Texas. What makes a severe thunderstorm different from the other types of events is that they generally travel through an area, bringing very intense weather conditions for a relatively short period of time at a general location. NWS and local weather reporting services can track the path of these storms and estimate the time when they will impact a specific location or roadway. An operator can capitalize on this ability to target appropriate responses ahead of and behind a storm.

Table 36 contains the generic concept of operations we developed for a severe thunderstorm event. The appropriate operator response should be geared toward the most prevalent (or severe) condition that exists for a particular roadway. For example, if high winds are the most prevalent condition, then the operator's response would be similar to those for a high-wind event. Likewise, if rainfall intensity creates severe ponding on a roadway, then the operator should implement the appropriate transportation management response for ponding.

Also note that the operator's response may change as the storm event progresses. For example, ahead of the storm, the operator may implement high wind or limited visibility responses. After the storm has passed, the operator may then need to implement responses because of ponding or flash flooding. It is critical that the operator not only monitor the path of the storm, but also assess the impacts of the storm even after it has passed.

Table 36. Concept of Operations for TMC Response to a Severe Thunderstorm.

Trigger	Actions
NWS Issues "Severe Thunderstorm Watch" Alert	• Continually monitor NWS for further alerts • Monitor RWIS stations for worsening weather conditions • Monitor TxDOT and OEM flood stations for potential flooding • Notify maintenance forces

NWS Issues "Severe Thunderstorm Warning" Alert	• Review local radar to determine:
	  o Direction of travel of storm (approaching or departing)
	  o Intensity and duration of event
	  o Roadway impacts
	  o Estimated arrival time
	• Monitor RWIS rain gauges for rainfall intensity rates and durations
	• Monitor RWIS wind sensors for high straight line winds
	• Verify weather impacting traffic operations using video surveillance

Limited Visibility Detected	• Use video surveillance to verify visibility condition • Issue speed advisory • Issue lane assignment advisory
Severe Ponding Detected	• Use video surveillance to verify severity • Issue speed advisory • Issue lane assignment advisory
Flash Flooding Detected or NWS Issues "Flash Flood Warning" or OEM Issues "Flash Flood Warning"	• Use video surveillance to verify location and severity of flooding • Dispatch service/courtesy patrols and maintenance forces to flood-prone areas • Implement lane closures procedures • Alert emergency responders and media to locations of known road closures due to flash flooding • Display known flooding locations on Internet traffic condition displays • Implement alternative route plan for large-scale roadway flooding
NWS High-Wind Advisory Straight Line Winds Detected	• Use RWIS to monitor for high-wind gusts, intensity, and direction • Issue wind advisory alert for high-profile vehicles, if appropriate
NWS Issues "Tornado Warning"	• Use video surveillance to verify location and direction of travel • Issue shelter warning on DMSs/HARs on appropriate roadways
NWS Cancels Warning or Intensity Wanes	• Return to normal operating status • Revise response as appropriate • Coordinate and prioritize clean-up locations with maintenance forces • Assist in implementing traffic control for clean-up efforts

TORNADOS

While not necessarily a rare event in Texas, managing traffic during tornado events is somewhat difficult because of the nature of tornados. Tornados are unpredictable – they form and dissipate suddenly, their path is erratic, they may vary in width from a couple of hundred feet to ½ mile or more, and they do not always form under the same circumstances. Because tornados generally occur in conjunction with other weather events (i.e., severe thunderstorms), the operator should also be monitoring the weather situation and actively managing traffic in the vicinity of the storm. Table 37 shows the concept of operations for managing traffic during a tornado event.

In providing a traffic management response to a tornado event, the overwhelming consensus of most TxDOT operators is that no response should be taken unless a tornado has been spotted on the ground and confirmed either by law enforcement personnel or by video surveillance; however, when a tornado has been spotted and confirmed, the operator should take action to manage traffic in the immediate area of the storm. Dynamic message signs and highway advisory radios should be used to alert travelers in the immediate path of the tornado to seek shelter. The primary focus area should be those roadways in the immediate path of the storm – roadways the tornado will cross in the next 15 minutes or so. The operator can use weather station reports and NWS storm predictions to determine which roadways are likely to be impacted within the next 15 minutes.

For travelers outside the impacted area, the traffic management objective should be to prevent travelers from entering the area. Operators should consider using their dynamic message signs and highway advisory radios to alert travelers outside the impacted area to seek alternate routes around the area or to tune to NWS radio to obtain up-to-date information about the storm. Because high winds are a common phenomenon with tornados, operators may want to consider issuing wind warning alerts for high-profile vehicles.

Once the storm has passed, the role of the operator should be to assist with the aftermath. It is highly likely that if a tornado passes over a freeway, debris will be present. The operator can take action to implement lane closures by posting messages alerting drivers to debris, and alerting maintenance forces as to the type and location of debris removal needs. As incidents and overturned vehicles may also have occurred, the operator may also need to dispatch emergency personnel and courtesy patrol vehicles to perform incident management functions and services (such as rendering aid, and establishing lane closures and detour routes).

Table 37. Concept of Operations for TMC Response to a Tornado Event.

Trigger	Actions
NWS Issues "Tornado Watch" Alert	• Continually monitor NWS for further alerts • Monitor RWIS stations for worsening weather conditions • Monitor TxDOT & OEM flood stations for potential flooding • Notify maintenance forces of potential tornadic activity in area

NWS Issues "Tornado Warning"	• Review local radar to determine the following:
	  o Direction of travel of storm (approaching or departing)
	  o Intensity and duration of event
	  o Roadway impacts
	  o Estimated arrival time
	• Monitor video surveillance to verify presence and path of tornado

Tornado Verified and Approaching Roadway	• Implement Tornado *ACTS* to accomplish the following:
	  o Alert travelers in path of storm to seek immediate shelter
	  o Encourage travelers outside path of storm to seek alternate route
	  o Encourage motorists approaching storm area to tune to radio for updated weather information
	  o Alert high-profile vehicles approaching storm area to the potential for high winds
	• Report specific locations of tornado to enforcement personnel
	• Alert maintenance forces to possibility of assistance with clean-up/debris removal

Tornado Passes	• Revise response appropriate for other events (e.g., severe ponding or incident conditions) • Coordinate and prioritize clean-up locations with maintenance forces • Dispatch tow truck operators to remove overturned/damaged vehicles • Notify emergency medical services (EMS) if emergency services necessary • Implement lane closure strategies for flooded lanes/debris
Tornado Warnings Canceled	• Dispatch service/courtesy patrols and maintenance forces to provide traffic control • Implement lane closures procedures for flooding or debris • Alert emergency responders media to locations of known road closures due to storm damage • Display known storm damage locations/closures on Internet traffic condition displays • Implement alternative route plan for wide-scale damage

WINTER STORM

Although winter storms primarily affect the northern and western districts in the state, every district is susceptible to damages and effects caused by winter storms. Except for the most southern districts, almost every district reported experiencing winter storm conditions at least once every year. The northern and Panhandle districts experience about three to five major winter storms per year. Typically winter storms can bring accumulations of one or more of the following: freezing rain and/or drizzle, sleet, and snow. These events can lead to ice forming on bridges and overpasses that can make travel potentially hazardous. Some winter storms are capable of producing strong winds, which can lead to overturned vehicles. Some winter storms, particularly ice storms, can lead to large amounts of broken tree limbs and debris accumulation on the roadways.

Most TxDOT districts have already developed procedures for managing traffic during winter storm conditions. For the most part, these procedures involve using maintenance forces to sand roadways and overpasses once ice has been detected. Several districts, including Houston, Wichita Falls, El Paso, and Amarillo, have installed ice detection technologies at key locations.

Table 38 shows the proposed concept of operations for TMC operators to manage traffic during snow and ice events. These actions are intended to supplement the processes and procedures that already exist in a district for responding to winter weather events, and are geared specifically toward the operator in the TMC – and not maintenance forces.

The primary objectives of the operator in the TMC are: 1) to assist maintenance forces in detecting locations where snow and ice accumulations make travel hazardous, and 2) to issue alerts and warnings to travelers of potentially hazardous locations. As winter storm conditions begin to occur in an area, control center operators, using video surveillance and pavement sensors, can identify locations where travelers are having trouble with slick pavements and can direct maintenance forces to the most impacted locations. As snow and ice begin to accumulate, the TMC operator can be responsible for managing the dissemination of road and bridge closures and can issue travel alerts, speed advisories, and lane and road closures using the dynamic message signs and highway advisory radios.

Table 38. Concept of Operations for TMC Response to a Snow/Ice Event.

Trigger	Actions
NWS Issues "Winter Storm Watch" Alert	• Review operational status of RWIS stations • Review communication status to DMS and HAR locations • Review preprogrammed snow/ice messages in DMS/HAR devices • Review contact information of emergency response personnel/dispatchers • Review preposition location for service/courtesy patrols
NWS Issues "Winter Storm Warning" Alert or Air Temperature Approaching Freezing	• Monitor rain gauge/precipitation sensors gusts from RWIS • Monitor thermometer from RWIS for air temperatures at or below freezing • Monitor video surveillance system • Monitor pavement temperature sensors for freezing conditions • Alert maintenance forces as to locations where pavement sensors/air temperatures are reaching the freezing point • Alert contract tow truck operators of potential icing locations
Ice/Snow Detected/ Reported	• Implement Snow/Ice *ACTS* to accomplish the following: o Advise travelers of locations where snow and ice conditions are occurring o Encourage travelers approaching winter storm area to seek alternate routes o Encourage travelers to delay entering winter storm area until conditions have improved o Increase traveler awareness of winter storm maintenance activities • Display known weather event alerts on Internet traffic condition displays
Ice/Snow Accumulation Detected/ Reported	• Alert media to known locations of snow and ice accumulations • Notify maintenance forces of locations where snow and ice accumulations have been detected/measured/observed • Implement Snow/Ice *ACTS* to accomplish the following: o Increase awareness of locations where snow and ice accumulations make travel hazardous o Restrict travel to specific lane or roadway where winter maintenance is being performed o Restrict travel to speeds appropriate for roadway surface/visibility conditions o Increase following distance separation between vehicles • Notify emergency services dispatchers of locations of snow and ice accumulations • Display known lane restrictions/closures on Internet traffic condition displays • Adjust responses as appropriate for conditions
Ice/Snow Accumulation Dissipates	• Return to normal operating status • Revise response as appropriate • Coordinate and prioritize clean-up locations with maintenance forces • Assist in implementing traffic control for clean-up efforts

CATALOG OF POTENTIAL TRAFFIC MANAGEMENT STRATEGIES

According to FHWA's *Weather-Responsive Traffic Management Concept of Operations* document (*22*), operational strategies can be divided into three categories:

- advisory strategies,
- control strategies, and
- treatment strategies.

Advisory strategies involve activating devices and systems that provide travelers with weather and traffic information. Notices may be broadcast directly to the public through dynamic message signs, highway advisory radio, Internet, etc. The objective is to warn travelers to take specific action in response to hazardous conditions created by an adverse road or weather conditions (e.g., reduce speed because of limited visibility). Other strategies are intended to advise motorists to keep from making a trip or entering into a hazardous situation (e.g., watch for high water on roadway). Advisory strategies also involve alerting and coordinating with other transportation agencies.

Control strategies involve altering the state roadway device that regulates traffic flow and roadway capacity during a weather event. The following are common control strategies used by transportation agencies:

- lowering freeway speed limits through the use of dynamic message signs or variable speed limit signs,
- modification of ramp metering rates or signal timing to slow the flow of traffic,
- use of flashing beacons and highway advisory radios to issue warnings, and
- use of a gate to physically prohibit entry into a hazardous area.

Treatment strategies involve using road maintenance resources applied directly to the roads to mitigate the impacts of weather events on transportation. For winter weather events, this might involve the deployment of sanding or deicing chemicals. For other types of events, this might involve the activation of sump pumps, the deployment of fog dispersion systems, etc. Many of the treatment strategies involve coordination of traffic, maintenance, and emergency management agencies.

To assist TxDOT in developing traffic management responses for weather events, we have developed a catalog of advisory, control, and treatment strategies (*ACTS*) that might be appropriate for TxDOT operators to take in response to particular weather events. Where appropriate, we have identified *ACTS* to be taken in the immediate area impacted by the weather events. We have also attempted to identify *ACTS* that might be appropriate to implement on roadways and traffic management devices outside of the immediate area of impact.

ADVISORY, CONTROL, AND TREATMENT STRATEGIES (*ACTS*) FOR WEATHER EVENTS

The following lists the advisory, control, and treatment strategies for different types of weather events.

Limited Visibility Events

Table 39 provides a summary of some of the *ACTS* that TxDOT could implement in response to limited visibility conditions. These *ACTS* are appropriate for limited visibility conditions caused by not only fog, but also blowing sand, smoke, heavy rainfall, or blowing snow. The exact content of the advisory messages should be adjusted to reflect the type of event causing the limited visibility conditions.

Ponding and Flash Flooding Events

Table 40 provides a summary of the *ACTS* that TxDOT could implement in response to ponding and flash flooding conditions. We recommend that a TxDOT operator consider implementing one or more of these *ACTS* when water in the wheel path begins impacting operations of the freeway.

High-Wind Events

Table 41 shows the *ACTS* that TxDOT operators could potentially implement in response to high-wind events.

Tornado Events

Table 42 shows the *ACTS* that TxDOT operators could potentially implement in response to tornado events. We recommend that TxDOT implement these *ACTS* only after an operator: 1) has confirmed the sighting of a tornado with a video surveillance camera, or 2) has received a confirmed report from an appropriate law enforcement or emergency management personnel.

Winter Storm Events

Table 43 shows the *ACTS* that TxDOT operators could potentially implement in response to winter storm events.

Table 39. Potential *ACTS* to Manage Operations during Limited Visibility Events.

Type of Action	Location	Strategy
Advisory	Inside Affected Area	• Post speed advisories appropriate for visibility conditions on DMSs • Use DMSs/HARs to alert motorists of end of queue locations or location of stopped vehicles • Use HARs to recommend motorists increase following distance between vehicles
	Outside Affected Area	• Issue alternative route advisories to keep vehicles from entering areas of limited visibility • Alert media to known locations of limited visibility • Display known limited visibility locations on Internet traffic condition displays
Control	Inside Affected Area	• On multilane facilities, use vehicle lane restrictions to separate trucks from passenger vehicles in traffic stream • For isolated or spot locations, implement pilot car operation using courtesy patrols, maintenance vehicles, and/or law enforcement vehicles • Increase vehicle and pedestrian clearance intervals at frontage road traffic signals • Reduce metering rate to restrict vehicles from entering freeway • When visibility limitations are severe, close ramps to prohibit vehicles from entering freeway
	Outside Affected Area	• Reduce metering rate to restrict vehicles from entering freeway • Implement pilot car operation to guide vehicles through impacted area
Treatment	Inside Affected Area	• Activate high mast or roadside safety lighting • Activate in-pavement lighting system • Predeploy courtesy/service patrols for rapid removal of stalled/disabled vehicles

Table 40. Potential *ACTS* to Manage Operations during Ponding/Flash Flooding Events.

Type of Action	Location	Strategy
Advisory	Inside Affected Area	• Post lane closure messages on DMSs immediately upstream of ponding/flash flood location • Use lane control signals to alert motorists as to which lanes are closed • Post speed advisories on DMSs for upstream traffic approaching ponding/flash flooding location • Use HARs to alert motorists as to which lanes are closed • Notify emergency responders about locations, limits, and lanes affected by ponding/flash flooding conditions
	Outside Affected Area	• Use DMS/HAR on connector facilities to notify travelers of ponding/flash flooding conditions • Alert media to known locations of ponding/flash flooding • Display known ponding/flash flooding locations on Internet traffic condition displays
Control	Inside Affected Area	• Request maintenance forces implement lane closure traffic control • Reduce metering rate to limit number of vehicles entering upstream of ponding/flash flooding locations • Implement alternative route plan for large-scale roadway flooding flash flooding conditions
	Outside Affected Area	• None
Treatment	Inside Affected Area	• Predeploy courtesy/service patrols for rapid removal of stalled/disabled vehicles • Request maintenance forces to mobilize pumping of water from travel lanes • Contact heavy-duty wreckers to remove stalled trucks for ponding/flash flooding area • Request maintenance forces to remove sediment and debris from travel lanes • Issue maintenance request to repair damaged pavement • Document the area. If a pattern can be established, then typically there is a bigger problem such as a partially collapsed pipe

Table 41. Potential *ACTS* to Manage Operations during High-Wind Events.

Type of Action	Location	Strategy
Advisory	Inside Affected Area	• Post speed advisories on DMSs immediately upstream of high wind locations • Use HARs to alert high-profile vehicles of appropriate detour route around high wind area • Notify emergency responders about locations, and facilities under high-wind warning restrictions/closures
	Outside Affected Area	• Post detour advisories on DMSs for upstream traffic approaching high-wind restriction/closure location • Alert media to known locations of high wind locations • Display known high wind locations on Internet traffic condition displays • Contact local commercial vehicle operators to high-wind closure/restriction locations
Control	Inside Affected Area	• Request maintenance forces implement lane closure traffic control • Implement alternative route plan for high-wind warning events • Notify enforcement personnel of appropriate travel speeds for high-wind conditions
	Outside Affected Area	• None
Treatment	Inside Affected Area	• Provide holding area for high-profile vehicles • Place maintenance forces on standby to remove debris • Contact heavy-duty wreckers to alert them to high-profile vehicle rollover potential • Issue maintenance request to repair damaged pavement due to incident

Table 42. Potential *ACTS* to Manage Operations during Tornado Events.

Type of Action	Location	Strategy
Advisory	Inside Affected Area	• Use DMSs/HARs to alert motorists to seek shelter immediately • Notify emergency responders that tornado has been visually verified using video surveillance • Notify maintenance forces of need for debris removal/lane closures
	Outside Affected Area	• Post detour advisories on DMSs and HARs for upstream traffic approaching tornado warning area • Post radio station frequency where motorists can obtain National Weather Service/emergency broadcast information on DMSs • Alert high-profile vehicles of potential for high winds in affected area • Display known weather event alerts on Internet traffic condition displays • Contact local commercial vehicle operators to high wind closure/restriction locations
Control	Inside Affected Area	• Request maintenance forces implement lane closure traffic control • Implement alternative route plan for high-wind/flooding warning events
	Outside Affected Area	• None
Treatment	Inside Affected Area	• Place maintenance forces on standby to remove debris • Contact heavy-duty wreckers to alert them to high-profile vehicle rollover potential • Issue maintenance request to repair damaged pavement due to debris/flooding, etc.
	Outside Affected Area	• Provide holding area for high-profile vehicles (such as rest area)

Table 43. Potential *ACTS* to Manage Operations during Winter Storm Events.

Type of Action	Location	Strategy
Advisory	Inside Affected Area	• Use DMSs to advise travelers to use speeds appropriate for current conditions • Use DMSs to notify travelers to use specific lanes for traveling • Use DMSs/HARs to alert travelers of specific locations of closures • Alert maintenance forces of known locations of snow and ice accumulations • Alert service patrols/tow contractors of known locations of snow and ice accumulations
	Outside Affected Area	• Post detour advisories on DMSs and HARs for upstream traffic approaching winter weather area • Post radio station frequency where motorists can obtain National Weather Service/emergency broadcast information on DMSs • Inform travelers to avoid unnecessary trips • Alert high-profile vehicles of potential for high winds in affected area (Winter Storm Warning) • Use DMSs/HARs to alert motorists to the presence of winter snow maintenance operations • Display known weather event alerts on Internet traffic condition displays
Control	Inside Affected Area	• Use lane control signals (LCSs) to restrict travel to specific lanes • Restrict access to freeway by closing entrance ramps • Close freeway to all travel due to hazardous travel conditions • Increase clearance interval on traffic signals
	Outside Affected Area	• Restrict access to authorized personnel in affected area through ramp and mainlane closures • Implement detour routes around icy bridge/steep grade locations
Treatment	Inside Affected Area	• For severe ice/snow events, pretreat pavement with deicing chemicals in advance • Contact heavy-duty wreckers to alert them to high-profile vehicle rollover potential • Issue maintenance request to reapply pavement treatment/sanding • Coordinate the deployment of maintenance trucks and prioritize treatment needs for affected areas
	Outside Affected Area	• Provide holding area for high-profile vehicles (such as rest area)

CANDIDATE DMS MESSAGES FOR SPECIFIC WEATHER EVENTS

As part of TxDOT Project 0-4023, TTI researchers developed a *Dynamic Message Sign Message Design and Display Manual* (*63*) for use by TxDOT personnel who have responsibility for the operation of and/or message design of large permanent DMSs and portable DMSs. The Manual is designed to help both new and experienced TMC operators develop properly formatted, meaningful messages for display on DMS signs. The Manual indicates that "Proper [message] design begins with understanding the basic information need of motorists." According to the Manual, dynamic message signs and other types of information dissemination devices need to provide drivers with the following in order to be effective:

- the type of problem (descriptor),
- the location of the problem,
- the number of lanes that are affected (closure description),
- the location of the lane closure,
- the effects on travel,
- the audience for the message,
- proper responses or driving actions to be taken by the motorist, and
- a reason for the motorist to follow the recommended driving action.

Because not all DMS messages can provide travelers with all this information at one time, an operator has to decide "what information is most important and how to present that information in a way that minimizes motorist misunderstanding and encourages them to take appropriate action" (*63*).

In addition to providing general guidelines for developing DMS messages, the Manual also provides guidance for designing messages for use when high water covers the freeway and frontage roads. As part of the 0-4023 project, the research team conducted motorist comprehension studies of messages for when water covers the freeway. These comprehension studies showed that drivers want to know the following when high water conditions exist but the freeway is still traversable:

- be alerted about the high water,
- know the location of the high water, and

- be confident that they can pass through and do not have to exit the freeway.

The study also found that when the water level increases to the point where the freeway is no longer passable, driver information needs change. The researchers suggest that when the roadway becomes impassable, drivers want to know the following:

- be alerted that the freeway is closed,
- know the location of the closure, and
- be informed as to which exit ramp to take.

Using these principles, we developed candidate messages that operators could use to effect different *ACTS* for different weather conditions. Figure 39 contains proposed DMS messages that can be employed in limited visibility situations. Figure 40 provides several proposed messages that can be used during ponding and flooding events, while Figure 41 shows proposed warning and speed advisory messages for use during high-wind events. Figure 42 contains messages that operators can use to manage traffic operations during tornado events. Figure 43 contains candidate message designs that could be used to manage traffic operations during winter storm events.

We should note that, while these messages were developed using the standard guidelines for DMS message designs, they have not been tested in a controlled laboratory environment. We strongly urge TxDOT to consider conducting human factors testing on these messages to ensure that their meaning cannot be misconstrued by the traveling public.

Warning Messages – This message to be displayed if operator wants to provide general warning messages due to limited visibility conditions.

I-10 EAST DENSE FOG USE CAUTION	I-10 EAST DENSE FOG REDUCE SPEED	I-10 EAST BLOWING SAND REDUCE SPEED

Speed Advisory Messages – This message to be displayed if operator wants to provide speed advisories due to limited visibility conditions.

I-10 EAST DENSE FOG ADVISE XX MPH	I-10 EAST DENSE SMOKE ADVISE XX MPH	I-10 EAST BLOWING SAND ADVISE XX MPH

End of Queue Warnings (Two Panel Message) – This message to be displayed to alert motorists of end of queue.

Panel 1	Panel 2	Panel 1	Panel 2
I-10 EAST DENSE FOG AHEAD	WATCH FOR STOPPED VEHICLES	I-10 EAST DENSE FOG NEXT X MILES	WATCH FOR STOPPED VEHICLES

Truck Lane Restriction (Two Panel Message) – This message to be displayed if operator wants to restrict heavy vehicles to particular lane.

Panel 1	Panel 2
I-10 EAST DENSE FOG AHEAD	TRUCKS RIGHT LANE ONLY

Roadway Closed – This message to be displayed when the roadway is closed due to limited visibility conditions.

I-10 EAST CLOSED EXIT AT VOSS

Diversion Message (Two Panel Message) – This message to be displayed to encourage diversion to alternate routes with roadway closed due to limited visibility conditions. These messages should be posted on signs outside the area impacted by the limited visibility conditions.

Panel 1	Panel 2
I-10 EAST CLOSED DENSE FOG	USE OTHER ROUTES

Figure 39. Candidate DMS Messages for Limited Visibility Conditions.

__Main Lanes Passable__ – This message to be displayed if there is water over the roadway, but roadway remains passable.

WATER ON ROAD AT VOSS RD USE LEFT LANE	WATER ON ROAD AT VOSS RD ADVISE XX MPH	WATER ON ROAD PAST VOSS EXIT REDUCE SPEED	WATER ON ROAD AT VOSS EXIT USE CAUTION

__Main Lanes Impassable__ – This message to be displayed if there is water over the roadway, and the roadway is impassable.

I-10 EAST CLOSED EXIT AT VOSS	I-10 EAST FLOODED EXIT AT VOSS	I-10 EAST CLOSED TAKE VOSS EXIT

__Frontage Road Impassable (Two Panel Message)__ – This message to be displayed when the frontage road is closed due to ponding or flash flooding.

Panel 1	Panel 2
FRONTAGE ROAD FLOODED AT VOSS	USE OTHER ROUTES

__Diversion Message (Two Panel Message)__ – This message to be displayed to encourage diversion to alternate routes with roadway closed due to ponding or flash flooding. These messages should be posted on signs __outside__ the area impacted by the ponding or flash flooding.

Panel 1	Panel 2	Panel 1	Panel 2
I-10 EAST CLOSED	USE OTHER ROUTES	I-10 EAST CLOSED	TAKE NEXT EXIT

Figure 40. Candidate DMS Messages for Ponding and Flash Flooding Conditions.

Speed Advisory for All Vehicles – This message to be displayed if operator wants to provide general speed advisory information due to high wind conditions.

I-10 EAST HIGH WINDS ADVISE XX MPH	I-10 EAST HIGH WINDS REDUCE SPEED

Speed Advisory for High-Profile Vehicles (Two Panel Message) – This message to be displayed if operator wants to provide specific speed advisories for high-profile vehicles.

Panel 1	Panel 2
I-10 EAST TRUCKS HIGH WINDS	MAX TRUCK SPEED XX MPH

Roadway Closed to High-Profile Vehicles (Two Panel Message) – This message to be displayed if roadway closed to high profile vehicles due to high winds.

Panel 1	Panel 2
I-10 EAST CLOSED TO TRUCKS	ALL TRUCKS EXIT AT VOSS

Roadway Closed to All Vehicles (Two Panel Message) – This message to be displayed if roadway closed to all vehicular traffic due to high winds.

Panel 1	Panel 2
I-10 EAST CLOSED HIGH WINDS	ALL TRAFFIC EXIT AT VOSS

Diversion Message (Two Panel Message) – This message to be displayed to encourage trucks to use alternate routes due to high wind conditions. These messages should be posted on signs outside the area impacted by high winds.

Panel 1	Panel 2
I-10 EAST HIGH WINDS AT VOSS	TRUCKS USE ALTERNATE ROUTE

Figure 41. Candidate DMS Messages for High-Wind Conditions.

Roadway In Path of Tornado – This message to be displayed if roadway is located in direct path of tornado.

I-10 EAST TORNADO APPROACHING	SEEK SHELTER IMMEDIATELY

Tornado Warning – High Wind Advisory Vehicles (Two Panel Message) – This message to be displayed to alert high-profile vehicles to expect high winds.

Panel 1	Panel 2
I-10 EAST TORNADO WARNING	EXPECT HIGH WINDS

Tornado Warning – Diversion Message (Two Panel Message) – This message to be displayed to alert motorists entering an area about a tornado warning and to advise motorists to seek alternate route.

Panel 1	Panel 2
I-10 EAST TORNADO WARNING	SEEK ALTERNATE ROUTE

Tornado Warning – Tune to Weather Alert Radio (Two Panel Message) – This message to be displayed to alert motorists entering an area to tune to particular radio station for alert information.

Panel 1	Panel 2
I-10 EAST TORNADO WARNING	TUNE RADIO TO XXXX AM

Tornado Warning – General Warning Message (Two Panel Message) – This message to be displayed to alert motorists entering an area that a tornado warning has been issued by NWS.

Panel 1	Panel 2
I-10 EAST SCHULLENBURG TRAFFIC	TORNADO WARNING USE CAUTION

Figure 42. Candidate DMS Messages for Tornado Conditions.

General Winter Storm Advisories – These messages to be displayed to alert motorists to general winter weather conditions on roadway.

I-10 EAST ICE / SNOW USE CAUTION	I-10 EAST ICE ON BRIDGES REDUCE SPEED	I-10 EAST WINTER CONDITIONS REDUCE SPEED

Winter Storm Conditions Present – Speed Advisory (Two Panel Message) – This message to be displayed to provide specific speed advisory in winter weather conditions.

Panel 1	Panel 2
I-10 EAST ICE ON ROADWAY	ADVISE XX MPH

Winter Storm Conditions Present – Restrict Traffic to Specific Lane (Two Panel Message) – This message to be displayed to restrict traffic to specific lane or lanes.

Panel 1	Panel 2
I-10 EAST ICE ON ROADWAY	ALL TRAFFIC USE RIGHT LANE

Winter Storm Conditions Present – Freeway Closed (Two Panel Message) – This message to be displayed to alert motorists that winter storm conditions have closed freeway.

Panel 1	Panel 2
I-10 EAST CLOSED WINTER STORM	EXIT AT VOSS

Winter Storm Conditions Present – Diversion Message (Two Panel Message) – This message to be displayed to advise motorists to use alternate routes or delay making trip.

Panel 1	Panel 2	Panel 1	Panel 2
I-10 EAST CLOSED WINTER STORM	USE ALTERNATE ROUTES	I-10 EAST WINTER STORM CONDITIONS	SEEK SHELTER

Winter Storm Conditions – General Warning Message (Two Panel Message) – This message to be displayed to alert motorists to tune radio to get weather information from NWS.

Panel 1	Panel 2
I-10 EAST WINTER STORM CONDITIONS	TUNE TO XXXX AM FOR INFO

Winter Storm Conditions – General Warning Message (Two Panel Message) – This message to be displayed to alert motorists to potential presence of winter maintenance vehicles.

Panel 1	Panel 2
I-10 EAST WINTER STORM CONDITIONS	WATCH FOR MAINTENANCE TRUCKS

Figure 43. Candidate DMS Messages for Winter Storm Conditions.

FRAMEWORK FOR INTEGRATING WEATHER INFORMATION

In general, constructing a framework for utilizing weather information as part of any decision-making process requires tasks to accomplish the following items:

- Access – identifying and retrieving the information source,
- Analysis – examining the information for pertinent weather information,
- Alert – identifying critical weather situations that require actions, and
- Action – using the weather information to disseminate information or effect changes.

The following sections briefly describe each aspect of this generic framework as well as diagram potential implementation strategies.

ACCESS TO WEATHER INFORMATION

Access to up-to-date weather information is a critical first step of any decision-making process. A variety of information sources are available, from both the public and private sectors. Several factors must be considered when choosing an information source, including timeliness, coverage, format, cost, and accuracy.

These factors are very important considerations. While television and/or radio broadcasts might be very specific to a region, and timely, they are difficult to incorporate into any type of automated process. Other sources, such as weather feeds commonly available on the Internet, are available in standardized formats, making them much easier to integrate as part of an overall automated process. However, these sources depend upon an Internet connection and continued access to communications, items which may be problematic in some severe weather events.

Certainly the most widespread information source comes from the National Weather Service, one of the agencies housed under the National Oceanic and Atmospheric Administration. The NWS makes available a wide variety of weather information, including hourly observed conditions and severe weather outlooks, watches, warnings, and advisories. This information is provided in a variety of formats, including:

- *HTML* – HyperText Markup Language – a web browser based information source,
- *XML* – eXtensible Markup Language – a self-describing information feed that can be used in a variety of programmatic applications,

- *RSS* – Really Simple Syndication or Rich Site Summary – a self-describing information feed geared to information aggregation applications. RSS is a specialized application of XML.
- *CAPS* – Common Alerts Protocol – a self-describing information feed that combines the machine readable information aspects of the XML/RSS feed, with the increased information detail of the HTML data feed.

The NWS information is freely available from the following location: http://www.weather.gov/alerts. Information is available on a state-by-state, or a county-by-county, basis. The use of either source provides the same information, although the level of processing to obtain regionally specific information differs. Information feeds are typically updated on a 1-minute time cycle.

Consideration could also be given to utilizing more than one weather information source, to achieve redundancy and perhaps even cross-check the reported information.

ANALYSIS OF WEATHER INFORMATION

Regardless of which information source is utilized, it will undoubtedly cover a large geographic region. Because weather can be a very localized event, it is important to consider the reported location of the weather event, as that will help determine the affected roadways and information dissemination needs. The smallest regional feed available from the NWS information feeds is a county basis. Specific events may be forecast to a smaller location, such as a city. This may prove to be effective for most applications, although supplemental, and even more localized, information may be useful for smaller scale events, such as localized high winds or severe thunderstorms.

When using an Internet available information source, the information must be 'parsed' or sifted to pick out the appropriate elements in an automated manner. In particular, the critical information is:

- county/location,
- alert type,
- start time,
- end time,

- affected cities, and
- description.

Several techniques and tools are available for parsing information and obtaining the key forecast elements. These tools can be broadly classified into two categories:

- Compilation-based programming tools – Software development tools such as Visual Studio have a capability to connect directly to the Internet source and retrieve the HTML source code. By carefully examining the structure of the HTML pages, specific information can be extracted programmatically. The disadvantage of this technique is that it requires the format of the web pages to be static.
- Interpretation-based programming tools – Scripting language tools such as PHP (**P**HP: **H**ypertext **P**reprocessor) are designed specifically to work in a web-based environment. PHP is developed based on Perl – a scripting language intended as a text processing and report-generating language. This technique is often used for rapid development where execution efficiency is not critical to the purpose of applications. The advantage of this technique is the structure of the HTML pages being extracted can be more dynamic.

Figure 44 shows a portion of the NWS weather information feed for Texas. Multiple alerts are contained within the file. As an example, the pertinent information for the alert in the Presidio Valley is:

- What: A flood warning
- Where: For the Presidio Valley
- When: Issued – September 7, 2006, 1:11:00
- When: Expires – September 11, 2006, 12:00:00
- Additional Information: http://www.srh.noaa.gov/maf/

```
  <?xml version="1.0" encoding="UTF-8" ?>
- <rss version="2.0" xmlns:dc="http://purl.org/dc/elements/1.1/">
  - <channel>
      <title>Texas - Current Watches, Warnings and Advisories for Texas Issued by the National Weather Service</title>
      <link>http://www.weather.gov/alerts/tx.html</link>
      <lastBuildDate>Thu, 07 Sep 2006 00:18:00 EDT</lastBuildDate>
      <ttl>4</ttl>
      <language>en-us</language>
      <managingEditor>robert.bunge@noaa.gov</managingEditor>
      <webMaster>w-nws.webmaster@noaa.gov</webMaster>
      <description>Current Watches, Warnings and Advisories for Texas Issued by the National Weather Service</description>
    - <image>
        <url>http://weather.gov/images/xml_logo.gif</url>
        <title>NOAA - National Weather Service</title>
        <link>http://weather.gov</link>
      </image>
    - <item>
        <title>Flood Warning - Presidio Valley, Marfa Plateau (Texas)</title>
        <link>http://www.weather.gov/alerts/TX.html#TXC377.MAFFLSMAF.011100</link>
        <description>FLOOD STATEMENT Issued At: 2006-09-07T01:11:00 Expired At: 2006-09-11T12:00:00 Issuing Weather Forecast Office Homepage:
          http://www.srh.noaa.gov/maf/</description>
      </item>
    - <item>
        <title>Short Term Forecast - Dallam (Texas)</title>
        <link>http://www.weather.gov/alerts/TX.html#TXZ001.AMANOWAMA.035900</link>
        <description>Short Term Forecast Issued At: 2006-09-07T03:59:00 Expired At: 2006-09-07T05:00:00 Issuing Weather Forecast Office Homepage:
          http://www.srh.noaa.gov/ama/</description>
      </item>
```


Figure 44. Sample RSS Weather Information Feed from NWS for Texas.

Understanding the difference between the available information feeds is important. As seen in Figure 44, the data are self-describing, using tags (identified with “<” and “>” symbols) that contain item descriptions, such as <title>, <description>, etc. In contrast, Figure 45 shows a portion of the HTML data feed. This feed is more readily usable within an Internet browser for viewing by a person. Ultimately, a combination of the information available from the data feeds may be necessary to identify the scope and region of the appropriate response.

Presidio Valley, Marfa Plateau (Texas)

```
FLOOD STATEMENT
NATIONAL WEATHER SERVICE MIDLAND/ODESSA TX
803 PM CDT WED SEP 06 2006
...THE RIVER FLOOD WARNING FOR THE RIO GRANDE AT CANDELARIA WILL
REMAIN IN EFFECT FOR THE NEXT FEW DAYS...
MINOR RIVER FLOODING CONTINUES ON THE RIO GRANDE AT CANDELARIA
WEDNESDAY EVENING...WITH A STAGE OF 8.7 FEET (2.7 METRES) RECORDED
AT 715 PM. THE RIO GRANDE AT CANDELARIA IS FORECAST TO REMAIN NEAR
OR SLIGHTLY ABOVE FLOOD STAGE THROUGH SUNDAY MORNING. KEEP IN MIND
THAT ANY ADDITIONAL RAINFALL ALONG THE RIO GRANDE OR ITS TRIBUTARIES
ABOVE CANDELARIA OVER THE NEXT FEW DAYS MAY RESULT IN HIGHER RIVER
LEVELS.
MOTORISTS ARE URGED TO HEED FLOOD WARNINGS.  IF YOU ENCOUNTER A
FLOODED STRETCH OF ROADWAY... DO NOT ATTEMPT TO CROSS IT.  YOUR
VEHICLE COULD BE SWEPT DOWNSTREAM IN RUSHING FLOODWATERS.
RIVER LEVELS ARE HIGH.  RANCHERS AND FARMERS SHOULD MOVE LIVESTOCK
AND MACHINERY AWAY FROM FLOOD PRONE AREAS IF TIME PERMITS.
KEEP IN MIND THAT ANY ADDITIONAL RAINFALL ACROSS THE AREA COULD
SIGNIFICANTLY CHANGE THE PRESENT FORECAST STAGE.
STAY TUNED TO NOAA WEATHER RADIO OR OTHER LOCAL MEDIA OUTLETS FOR THE
LATEST INFORMATION ON THIS SITUATION. OR CONTACT THE NATIONAL WEATHER
SERVICE OFFICE IN MIDLAND AT 1.800.597.3220.
A FOLLOWUP PRODUCT WILL BE ISSUED THURSDAY MORNING.
TXC377-071303-
/X.EXT.KMAF.FL.W.0007.000000T0000Z-060911T1200Z/
/CDET2.2.ER.060830T2045Z.060902T0430Z.060910T1200Z.NO/
803 PM CDT WED SEP 06 2006
...FLOOD WARNING CONTINUES UNTIL SUNDAY MORNING...THE FLOOD
WARNING CONTINUES FOR THE RIO GRANDE AT CANDELARIA
* UNTIL SUNDAY MORNING
* AT 7 PM WEDNESDAY THE STAGE WAS 8.7 FEET (2.7 METERS).
* MINOR FLOODING IS OCCURRING AND MINOR FLOODING IS FORECAST
* FLOOD STAGE IS 8.7 FEET (2.7 METERS).
* AT 8.7 FEET...THE RIVER REACHES FLOOD STAGE.  MINOR FLOODING OF THE
RIVER ROAD IN LOW AREAS IS POSSIBLE. HOMES IN CANDALARIA ARE NOT
EXPECTED TO BE AFFECTED. FARMERS AND RANCHERS NEED TO REMAIN ALERT
TO THE WEATHER AND RIVER CONDITIONS AS LIVESTOCK AND MACHINERY MAY
```

Figure 45. Sample HTML Weather Information Feed from NWS for Texas.

CREATING ALERTS FROM WEATHER INFORMATION

Within the framework of integrating weather information into a management center, the ideal application is for electronic transfer and programmatic analysis. The use of human operators to examine the information on a recurring basis is inefficient and may not be able to be accomplished, given normal operator workloads from other traffic management tasks. Ideally, a software program parses the data feed and interacts with a comprehensive weather events database, which stores all of the information pertaining to alerts.

Because the information feed is updated on a regular basis (typically once per minute), numerous information updates will typically be received during a weather event. It is important for the database to have embedded logic that identifies if an alert is a new alert, an update to an existing alert (i.e., a change in conditions), an expired alert, or the same information as was reported previously. Subsequent to the initial condition, the database logic should only pass on information that is a new or changed condition.

CREATING ACTIONS FROM WEATHER EVENTS

The final step in the framework is taking the output from the database logic process and creating an alert for the operator. At a minimum, this alert must contain the following information:

- county/location,
- alert type,
- information (condition, start time, end time, affected locations),
- condition change (if applicable), and
- information change (if applicable).

The bottom two bullets are critical items to include, and specifically call attention to, if the weather event information changes. There are numerous situations that could account for this need, such as a change in severity (watch to warning), an update of affected locations, a change in event expiration times, etc.

GENERIC FRAMEWORK FOR INTEGRATION OF WEATHER EVENTS

Because the integration of, and reaction to, weather information is a relatively new consideration in traffic operations, the integration framework was diagrammed as both a short-term and long-term effort.

The short-term effort, shown in Figure 46, addresses each of the tasks identified at the start of this discussion. In the diagram, the information access is shown to be the NWS RSS feed, although it could be any information source. As presented in the analysis discussion, the information is parsed to create alerts, which are then passed to an alerts database. The alerts database utilizes embedded logic to identify the critical information to pass on to an operator, which would be new alerts, expired alerts, or a change in alert conditions. Each of these situations could conceivably cause an operator to take action.

The final step in Figure 46 shows the process of physically alerting an operator to a condition that needs attention. While the diagram shows this alert as a pop-up on the traffic operations software, it could also be an audible alert, a new icon, or some other standard mechanism of providing information to an operator concentrating on other tasks.

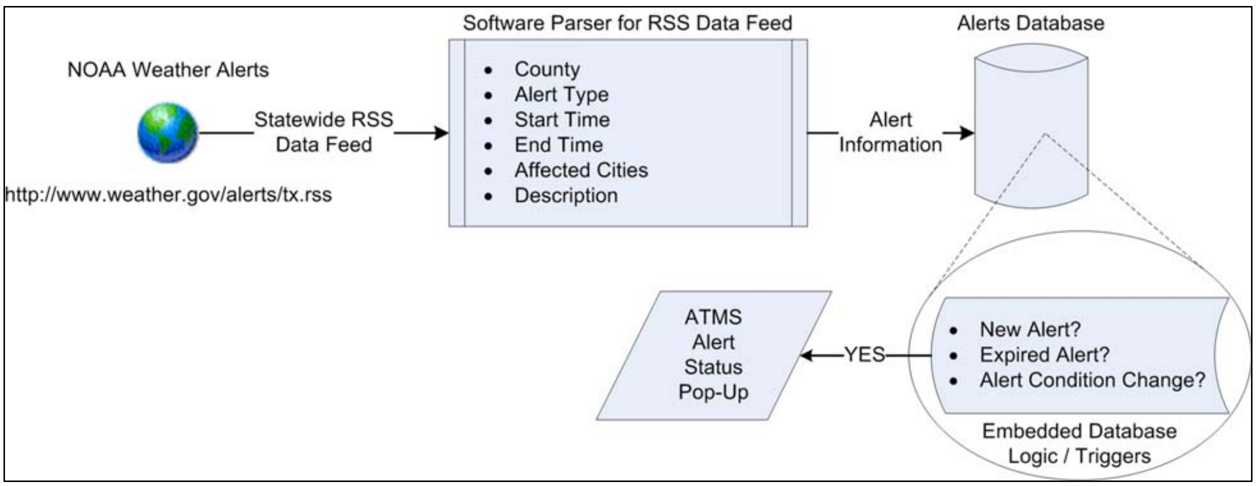


Figure 46. Short-Term Integration Framework.

Figure 47 shows a diagram of a longer-term integration approach, where additional logic and resources may be added to the process of determining when an operator should perform an action in response to a weather alert. Additional logic to coordinate and prioritize response scenarios may also be needed when multiple weather events occur in a short period of time. As seen in the diagram, in this long-term framework, the alert information from the database is sent through an additional processing step to determine a more explicit response scenario, in either timeframe or location.

Consider, as an example, a weather event of several thunderstorms in one quadrant of a large city. In the short-term integration, the NWS information simply provides the city name and the operator has to make determinations as to which portions of the monitored roadway network are affected, where to provide information alerts, what type of information alerts to provide, and potentially, even what vehicles to alert.

In the long term, as this process gets more commonplace and the analysis is supported by additional data, intelligent software may be able to provide increased guidance to operators. Based, for example, on the path and speed of a storm front, it may be possible to determine what roadway will be affected, and for what timeframe. That information could then be matched to the roadway infrastructure database, to provide suggestions to the operator for what resources could be used for notifying roadway users of the impending weather event.

It should be noted that the knowledge and logic flows represented in Figure 47 do not exist today. Additional research would be necessary to accomplish this level of integration and weather event prediction – in effect, combining aspects of meteorology and traffic operations.

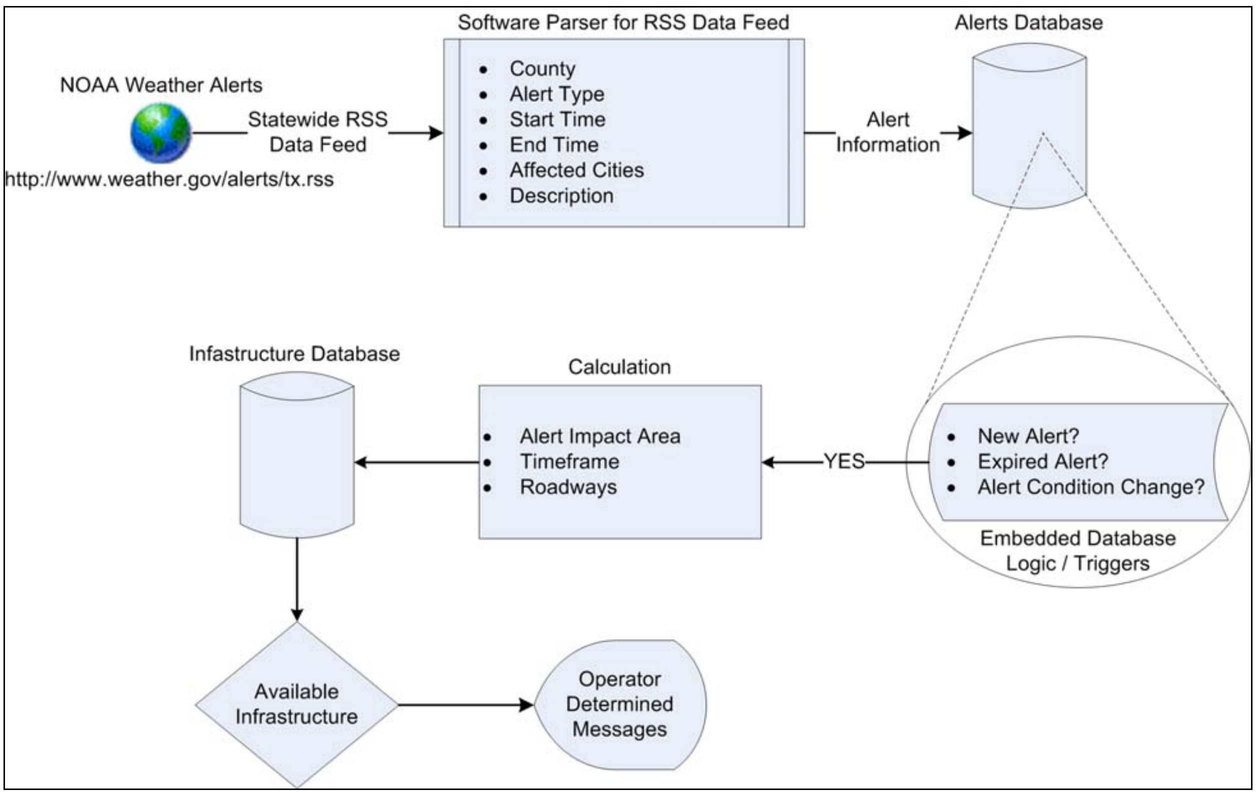


Figure 47. Long-Term Integration Framework.

SUMMARY AND RECOMMENDATIONS

Weather, and its impact on traffic operations, continues to be a concern to TxDOT and other operators of the transportation system. The goal of this research was to help TxDOT develop a structured, systematic approach for managing traffic during weather events. Our focus in this research project was on common weather events – such as fog, high winds, heavy rains, and snow and ice storms – that impact traffic operations day-to-day. First, we conducted a survey of selected TxDOT districts to determine what information TMC operators need to manage traffic operations during weather events. Through a review of the existing literature, we assessed systems and technologies that other states have deployed to manage traffic during weather-related events. We reviewed the current state of weather-related detection and monitoring technologies. Using historical traffic detector and weather information, we assessed the magnitude of the impact of different weather events on traffic operations. Using all this information, we developed concepts of operations for how TMC operators should respond to different types of weather-related events, including limited visibility conditions, ponding and flash flooding, high winds, severe thunderstorms, tornados, and winter storms. We developed a catalog of advisory, control, and treatment strategies (or *ACTS*) that operators could use to manage traffic operations during weather events. Specific criteria outline when TxDOT TMC operators should implement different types of responses. We proposed messages that TxDOT TMC operators can use on dynamic message signs to achieve different advisory and control strategies for different types of weather events. Finally, we provided a framework TxDOT can use to integrate weather information from the National Weather Service and other private weather providers into its TMC operations software.

RECOMMENDATIONS

The following are some of the general recommendations that we derived by conducting this research.

- TxDOT should consider expanding monitoring and dissemination of statewide weather information. While many districts have deployed weather monitoring technologies for specific purposes, there has been little effort to collect and disseminate this information on a statewide basis. TxDOT should strongly consider linking the various weather monitoring systems that have been deployed in individual districts throughout the state and disseminate this information through their statewide Roadway Conditions Internet website.

- Several TxDOT districts have developed strategies and deployed technology for managing traffic operations for specific weather events. These systems and management strategies have been developed to generally meet the needs of individual districts. So that driver expectation can be maintained throughout the state, TxDOT should develop formalized consistent management practices for all types of weather events. This research provided generic concepts of operations and a catalog of potential advisory, control, and treatment strategies that TxDOT can use as a foundation for developing statewide management practices.
- As one of its new initiative areas, the Federal Highway Administration is placing a greater emphasis on road weather management. This new initiative, Clarus (which is Latin for "clear"), is to develop and demonstrate an integrated surface transportation weather observing, forecasting, and data management system, and to establish a partnership to create a Nationwide Surface Transportation Weather Observing and Forecasting System. The objective of Clarus is to provide information to all transportation managers and users to alleviate the effects of adverse weather (e.g., fatalities, injuries, and delays). TxDOT should continue to monitor and participate in this initiative.
- Weather can have a far-reaching effect on traffic operations. Motorists in one district often require information about weather and travel conditions in other districts, particularly along routes used for intrastate and interstate travel. TxDOT has an obligation to provide these travelers with current, up-to-date alerts and warning information about developing weather situations, so they can make intelligent, informed travel decisions. TxDOT should implement operating agreements between districts as to what weather information should be disseminated and when. This includes determining what information is shared between district traffic management centers as well as what messages should be posted on DMSs under specific weather situations.

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APPENDIX A. FORM USED IN SITE VISIT INTERVIEWS

Identification of TxDOT Weather Information Needs

Name__________________________________ Location_____________________

Telephone______________________________

e-mail____
(if you prefer you may just attach a business card)

The following questions will help identify and assess the information needs and requirements regarding weather events. A weather event for the purposes of this assessment is an occurrence of weather that significantly impacts TxDOT operations, safety, and maintenance or impedes public travel on Texas roadways.

1. Do you have significant weather events that occur in your District?

___yes ____no ____unsure

2. Which of the following weather events occur in your District and what is the frequency of their occurrence? Please check all that apply

	Frequency of Occurrence			
Event	**1 to 2 years**	**1-2 times year**	**2 -4 times per year**	**4 or more times per year**
Snowfall				
Icy Roads				
Dense Fog				
Dust Storms				
High Winds				
Tornados				
Flash Flooding				
Flooded Roads due to Rising Water				

3. Which weather event is **most prevalent** in your district? ______________________________

4. How does this event affect you?

a. Daily roadway operations are affected____________

b. Safety of traveling public is affected_______________

c. Emergency management procedures are required_______________

d. Before event special maintenance and operations measures are required___________

e. During event special maintenance and operations measures are required___________

f. Post event special maintenance and operations measures are required___________

5. If you had additional weather information about this event would it influence your decision making regarding this event? ____________________ If yes, what amount of lead time do you need to maximize your effectiveness in dealing with this weather event?____________________

6. How specific must the forecast be to maximize your effectiveness? ____________________

7. What if any special information prior to the weather occurrence would assist in your district in dealing with this weather event?____

____

8. Do you currently have any TxDOT owned weather devices? _____yes _____no

If yes, please specify____

9. Are the weather devices isolated location devices or a part of a network?

_____isolated _________ part of a network ________other

10. Are there any devices in your area that are used by other agencies to monitor rain, ice, wind, etc. that you know of ____yes_____no If yes, which agency?________________________

11. Assessment of available devices

	Yes	No
Does the device work well?		
Is it reliable?		
Is it in the right location?		
Does it provide the right type of information?		
Do you use this device to make operational decisions?		

12. Do you use weather devices to make operational decisions? _____yes _____no

If yes, what types of actions do you take? (please check those that apply)

Deploy DMS? _________ Call local PD__________ Call Maintenance Staff?_________

Other____

13. Is there a written plan for the concept of operations during weather events? (Such as if it rains x amount call Y, if z amount call N) _____yes _____no

14. If there are No written plans are there informal and/or consistent responses to given events?

____yes ____no ___unsure

15. Comments____

____

APPENDIX B. COMPARISON OF CHARACTERISTICS AND PERFORMANCE SPECIFICATIONS OF SELECT WEATHER SENSING TECHNOLOGIES

Table B - 1. Comparison of Wind Sensor Technologies.

Product Name	LOA-004 (Long Baseline Optical Anemometer & Turbulence Sensors	RM Young Wind Speed/Direction Sensor Model #05103	Vaisala Ultrasonic Wind Sensor WS425	Vaisala Mechanical Wind Sensor WM30	Viasala Combined Wind Sensor Set
Manufacturer	Optical Scientific, Inc.	RM Young	Vaisala	Vaisala	Vaisala
Technology	Optical scintillation	Four-blade helicoids propeller	Ultrasonic Wind Sensor	Rotating cup anemometer[2] and wind vane[3]	A set consists of anemometer WAA151, wind vane WAV151, and wind transmitter WAT12[4]
RELIABILITY & MAINTENANCE					
MTBF (hr) [1]	NA	NA	227760	NA	NA
Maintenance/ Calibration	NA	Bearing inspection every 24 months	No maintenance needed	NA	NA
DATA					
Reports	Path integrated crosswinds, turbulence intensity	Wind speed and azimuth	Wind speed and direction	Wind speed and direction	Wind speed and direction
Update Rate	NA	NA	1-sec.	NA	NA
Interface	RS-232 ASCII	Wind speed: agnetically induced AV voltage Azimuth: analog DC voltage from conductive plastic potentiometer	SDI-12, RS-232, RS-485, RS-422	5-pin mail [Author: male?] with 12 mm threads	Output from WAT12: two analog current loops (speed and direction)
PERFORMANCE					
Measurement Range	0.1 to 40 m/s	0 to 134 mph (60 m/s)	Serial output: 0 to 144 mph (65 m/s); Analog output: 0 to 124 mph (56 m/s)	0.5 to 60 m/s	Speed: 0.4 to 75 m/s Direction: 0 to 360 degrees
Wind Speed Accuracy	NA	±0.6 mph (0.3 m/s)	±0.3 mph or 3% of reading, whichever is greater	±0.3 mph or 2% of reading, whichever is greater	±0.5 m/s or better
Wind Direction Accuracy	NA	±3 degrees	±2 degrees (over 1 m/s)	±3 degrees	±3 degrees
Gust Survival	NA	220 mph (100 m/s)	NA	NA	
Reference	www.opticalscientific.com	http://www.youngusa.com/	www.vaisala.com	www.vaisala.com	www.vaisala.com

Notes:
[1] MTBF = Mean Time Between Failures [2] Wind speed is recorded either by counting the number of pulses per unit time or by measuring the time between successive pulses.
[3] With constant voltage supplied to the potentiometer, the output voltage is directly proportional to the azimuth angle.
[4] WAT12 converts digital data supplied by WAA151 and WAV 131 into standard analog outputs (speed/direction).

Table B - 2. Comparison of Pavement Sensor Technologies.

Product Name	FP 2000	Frensor® Active Surface Sensor	Frensor® MK II	Sub-Surface Temperature Probe Model # S16UG-D
Manufacturer	Surface Systems, Inc.	Aerotech Telub AB	AerotechTelub AB	Surface Systems, Inc.
Technology	Passive	Active [2]	Active [3]	NA
RELIABILITY & MAINTENANCE				
MTBF (hr) [1]	40000	NA	NA	87600
Maintenance/Calibration	NA	NA	NA	Not required
DATA				
Reports	Pavement surface temperature; Wet/Dry; Chemical Wet, Snow/Ice Warning, Snow/Ice Watch	Freezing point for any combination of anti-icing/deicing chemicals	Freezing point for any combination of anti-icing/deicing chemicals	Temperature 17 inches below the roadway surface
Detected Chemicals	Sodium Chloride; Potassium Acetate; Magnesium Chloride in sufficient liquid solution	NA	NA	NA
Interface	SSI Type IIA	Serial RS-232 command interpreter	Serial RS-232 command interpreter	SSI Type IIA
PERFORMANCE				
Measurement Range	NA	NA	NA	NA
Accuracy	NA	NA	NA	NA
Freezing Point Range	-5 to 32 F	-4 to 32 F	-4 to 32 F	NA
Depth Range	NA	NA	NA	NA
Depth Accuracy	NA	NA	NA	NA
Detection Time	NA	3 secs to several minutes depending on conditions (normally 10 to 30 secs)	3 secs to several minutes depending on conditions (normally 10 to 30 secs)	NA
Comments	NA	NA	NA	Useful for pavement forecasting model and frost depth information
Reference	www.ssiweather.com	www.ssiweather.com	www.rwis.net	www.ssiweather.com

Notes:

[1] MTBF = Mean Time Between Failures

[2] A small peltier cell holds a sample of the water and salt on the road surface and cools the sample to freezing; the actual detection point is after the small rise in temperature when the supercooled liquid freezes at the freezing point.

[3] Improved version of Frensor® designed to handle the requirements stated by the U.S. market. Mobile Frensor® can be used to make freezing point mapping to determine the optimal amount of deicing fluid spread or identify optimal sensor locations.

Table B - 2. Comparison of Pavement Sensor Technologies (Cont.).

Product Name	Groundhog® Permanent Count Station (PCS)	Ultrasonic Depth Sensor	Vaisala DRS511/DRS511B	GFS3000PFD (Passive Freezing Point Detection)
Manufacturer	Nu-Meterics	Judd Communications	Vaisala	Boschung
Technology	Passive	Ultrasonic Pulse	Thermally passive [2]	BOPAS passive pavement sensor
RELIABILITY & MAINTENANCE				
MTBF (hr) [1]	100000	NA	NA	87600
Maintenance/ Calibration	Replace battery every 3 to 5 yrs	Check desiccant pack and solar radiation shield	MTTR: 3 hrs.	NA
DATA				
Reports	*Traffic*: count, speed, length, occupancy, (polling intervals 1 to 120 minutes); *Weather*: chemical index (passive detection) road surface temperature, wet/dry	Distance, Air temperature	Optical detection of the coverage [3], surface conductivity and electrochemical polarizability[4], surface capacitance[5], surface temperature, and ground temperature (-6 cm)	Pavement temperature, pavement status (dry, humid, etc), water thickness, freezing point temperature, salt factor/chemical concentration, remaining quantity of salt
Detected Chemicals	NA	NA	NA	NA
Interface	Wireless RFM 2.45 GHZ	Analog signal of 0 to 2.5 V or 0 to 5 V and ASCII digital output	NA	RS-232, RS-485, leased or commuted line, built-in radio
PERFORMANCE				
Measurement Range	NA	NA	Water layer thickness: 0 to 8 mm	NA
Accuracy	NA	NA	Water layer thickness: 0.1 mm for 0.0 to 1.0 mm	NA
Freezing Point Range	NA	NA	NA	NA
Depth Range	NA	1.6 to 32.6 ft	NA	NA
Depth Accuracy	NA	±1 cm or 0.4% distance to target	NA	NA
Detection Time	NA	NA	NA	NA
Comments	NA	Commonly used for snow depth measurement but can be applied to water levels as well. Depth sensor must be mounted perpendicular to the target.	Designed for use with Vaisala ROSA Road Weather Station. Able to detect black ice. Model DRS511B is designed for bridges.	Entry-level mode. Features three alarm levels. Able to discriminate between black ice, icy road, and frozen snow.
Reference	www.nu-metrics.com	www.juddcomm.com	www.vaisala.net	www.boschungamerica.com

Notes: [1] MTBF = Mean Time Between Failures. [2] A small peltier cell holds a sample of the water and salt on the road surface and cools the sample to freezing; the actual detection point is after the small rise in temperature when the supercooled liquid freezes at the freezing point. [3] To determine water thickness and ice/snow coverage [4] To determine the amount of deicing chemicals, freezing temperature, risk of ice formation. [5] Black ice detection.

Table B - 2. Comparison of Pavement Sensor Technologies (Cont.).

Product Name	GFS3000 AWS (Active Warning System)	GFS3000 AFM (Active Freezing Point Measurement)	GFS3000 AAM (Active Active Managmeent)
Manufacturer	Boschung	Boschung	Boschung
Technology	BOSO active pavement sensor	BOPAS (passive) and ARCTIS (active) pavement sensors.[2]	BOPAS (passive) and ARCTIS (active) pavement sensors.[3]
RELIABILITY & MAINTENANCE			
MTBF (hr) [1]	NA	NA	NA
Maintenance/ Calibration	NA	NA	NA
DATA			
Reports	Pavement temperature, pavement status (dry, humid, etc.), water thickness, freezing point temperature (calculated), salt factor/chemical concentration	Pavement temperature, pavement status (dry, humid, etc.) water thickness, freezing point temperature (calculated), salt factor/chemical concentration, remaining quantity of salt	Pavement temperature, pavement status (dry, humid, etc.), water thickness, freezing point temperature (calculated), salt factor/chemical concentration, remaining quantity of salt
Detected Chemicals	NA	NA	NA
Interface	Boschung communication board, RS-232, RS-485, leased or commuted line, built-in radio communication	Boschung communication board, RS-232, RS-485, leased or commuted line, built-in radio communication	Boschung communication board, RS-232, RS-485, leased or commuted line, built-in radio communication
PERFORMANCE			
Measurement Range	NA	NA	NA
Accuracy	NA	NA	NA
Freezing Point Range	NA	NA	NA
Depth Range	NA	NA	NA
Depth Accuracy	NA	NA	NA
Detection Time	NA	NA	NA
Comments	Features three alarm levels for present time and forecast. Able to discriminate between black ice, icy road, and frozen snow. Measured ice warning feature (alarm 2)	Features three alarm levels for present time and forecast. Able to discriminate between black ice, icy road, and frozen snow.	Features three alarm levels for present time and forecast. Able to discriminate between black ice, icy road, and frozen snow.
Reference	www.boshungamerica.com	www.boshungamerica.com	www.boshungamerica.com

Notes: [1] MTBF = Mean Time Between Failures
[2] The freezing point is measured by artificially cooling a small area on the surface of the sensor below the temperature of the pavement.
[3] The parallel cycling processes allow for a quick response time.

Table B - 3. Comparison of Visibility Sensor Technologies.

Product Name	VIS (Visibility Sensor)	Visibility Sensor Model 6230A	Visibility Sensor Model 6000
Manufacturer	Optical Scientific, Inc. (OSI)	Belfort Instrument	Belfort Instrument
Technology	NA	Forward scatter principle	Forward scatter principle
RELIABILITY & MAINTENANCE			
MTBF (hr) [1]	NA	87600	NA
Maintenance/ Calibration	NA	NA	NA
DATA			
Reports	Visibility (feet or meters)	Visibility	Visibility
Update rate	NA	NA	NA
Interface	RS-232	RS-232C @ 2400 baud	RS-232, RS-485, 300 to 38400 baud
PERFORMANCE			
Measurement Range	0.001 to 1 mile	17 ft to 30 miles	20 ft to 10 miles
Accuracy	20% up to 3 km	±10% of reading	±10% or 10 ft
Comments	Same technology as WIVIS® but without weather identifier	NA	This model includes two alarm outputs, which can be adjusted to alarm at user preset visibility thresholds
Reference	www.opticalscientific.com	www.belfortinstrument.com	www.belfortinstrument.com

Notes:
[1] MTBF = Mean Time Between Failures

Table B - 4. Comparison of Weather Identifier Plus Visibility Sensor Technologies.

Product Name	WIVIS ®(Weather Identifier and Visibility Sensor)	OWI™ (Optical Weather Identifier)	LEDWI® (Light Emitting Diode Weather Identifier)
Manufacturer	Optical Scientific, Inc. (OSI)	Optical Scientific, Inc. (OSI)	Optical Scientific, Inc. (OSI)
Technology	Uses the principle of optical scintillation to measure precipitation	NA	OSI's patented scintillation theory and opto-electronic technology for the identification of precipitation type
RELIABILITY & MAINTENANCE			
MTBF (hr) [1]	35000	NA	NA
Maintenance/ Calibration	Field calibration every two years: optics cleaning every six months	NA	NA
DATA			
Reports	Visibility , precipitation occurrence, precipitation type and intensity, NWS and WMO codes	Precipitation occurrence, precipitation type and intensity, NWS and WMO codes	Precipitation type
Present weather type identification	Rain, snow, drizzle, mixed, hail[2], ice, pellets[2]	Rain, snow, drizzle, mixed, hail[2], ice, pellets[2]	NA
Update rate	1 minute	1 minute	NA
Interface	RS-232	RS-232C	RS-232
PERFORMANCE			
Rain range	0.1 to 3000 mm/hr	0.1 to 3000 mm/hr	0.25 to 3000 mm/hr
Rain accuracy	5% accumulation	5% accumulation	NA
Snow range	0.01 to 50 mm/hr water eq.	0.01 to 50 mm/hr water eq.	0.05 to 1000 mm/hr water eq.
Snow accuracy	20% accumulation[3]	20% accumulation[3]	NA
Visibility range	0.001 to 1 mile (7 miles optional)	NA	NA
Visibility accuracy	20% up to 3 km	NA	NA
Comments	Widely used in several RWIS in the states	Same technology as WIVIS® but without visibility sensor	NA
Reference	www.opticalscientific.com	www.opticalscientific.com	www.opticalscientific.com

Notes:
[1] MTBF = Mean Time Between Failures
[2] with optional HIP-100 sensor attachment
[3] depends on snow density

Table B - 4. Comparison of Weather Identifier Plus Visibility Sensor Technologies (Cont.).

Product Name	Scintec Parsivek® M300 (Optical Precipitation Sensor)	Optical Precipitation Sensor (ORG®-815)	ETI Optical Infrared Y/N Precipitation Sensor
Manufacturer	Scintec AG	Optical Scientific, Inc. (OSI)	NA
Technology	Infrared laser band is used to measure variation in the detected radiation intensities	Scintillation technology	Dual beam infrared
RELIABILITY & MAINTENANCE			
MTBF (hr) [1]	NA	NA	NA
Maintenance/ Calibration	NA	NA	NA
DATA			
Reports	Particle size and velocity, precipitation rate and accumulated precipitation amount, precipitation kinetic energy, precipitation code according to WMO table 4680, visibility through precipitation, radar reflectivity	Rain rate (not accumulation)	Yes/No precipitation state
Present weather type identification	According to WMO table 4860	NA	NA
Update rate	10 to 999s	NA	NA
Interface	RS-232	RS-232C	Analog 2.2 V DC
PERFORMANCE			
Precipitation range	0.01 to 999.99 mm/hr	NA	Detectable particle size of 0/010 inch to large hail stones
Rain range	NA	0.1 to 500 mm/hr	
Rain accuracy	NA	NA	NA
Snow range	NA	NA	NA
Snow accuracy	NA	NA	NA
Visibility range	1 to 99999 m	NA	NA
Visibility accuracy	NA	NA	NA
Comments	NA	NA	NA
Reference	www.scintec.com	www.opticalscientific.com	www.ssiweather.com

Notes:
[1] MTBF = Mean Time Between Failures

Table B - 4. Comparison of Weather Identifier Plus Visibility Sensor Technologies (Cont.).

Product Name	Young Tipping Bucket Rain Gauge	Vaisala Weather Sensor FD12P	Vaisala FWD12	Vaisala FWD22
Manufacturer	R.M. Young Company	Vaisala	Vaisala	Vaisala
Technology	Tipping bucket mechanism	Optical forward scatter, analog capacitive surface sensor, temperature sensor	Forward scatter measurement	Forward scatter measurement
RELIABILITY & MAINTENANCE				
MTBF (hr) [1]	NA	NA	NA	NA
Maintenance/ Calibration	NA	NA	NA	NA
DATA				
Reports	Precipitation amount	Visibility; precipitation type and intensity; precipitation accumulation; present weather in SYNOP, METAR, and NWS codes	4 different precipitation types; precipitation intensity and accumulation; present weather; visibility	7 different precipitation types; precipitation intensity and accumulation; present weather; visibility
Present weather type identification	NA	11 different precipitation types; 52 codes from WMO code table 4680 and 4678 and NWS codes	Precipitation[2], fog, mist, haze[3], or clear; 36 codes from WMO 4680 code table	Precipitation[4], fog, mist, haze[3], or clear; 49 codes from WMO 4680 code table
Update rate	NA	NA	NA	NA
Interface	Magnetic reed switch	RS-232, RS-485	RS-232, RS-485	RS-232, RS-485
PERFORMANCE				
Precipitation range	0.01 mm per tip	0 to 999 mm/hr	NA	NA
Precipitation accuracy	2% up to 25 mm/hr	Detected above 0/05 mm/hr, within 10 minutes	Detected above 0/05 mm/hr, within 10 minutes	Detected above 0/05 mm/hr, within 10 minutes
Snow range	NA	NA	NA	NA
Snow accuracy	NA	NA	NA	NA
Visibility range	NA	10 to 50000 m	32 to 65600 ft (10 to 20000 m)	32 to 65600 ft (10 to 20000 m)
Visibility accuracy	NA	±4%	±10% for 10 to 10000 m; ±15% 10 to 20 km	±10% for 10 to 10000 m; ±15% 10 to 20 km
Comments	NA	NA	Programmable visibility alarm thresholds	Programmable visibility alarm thresholds
Reference	www.youngusa.com	www.vaisala.com	www.vaisala.com	

Notes:
[1] MTBF = Mean Time Between Failures; [2] rain, drizzle, mixed rain/snow; [3] smoke and sand; [4] rain, freezing rain, drizzle, freezing drizzle, mixed rain/snow, snow, ice pellets