Evaluation of the Utah DOT Weather Operations/RWIS Program on Traffic Operations

Final Report
November 2009

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16. Abstract

The transportation community has been aware of the impacts of adverse weather on the roadway system and that the use of weather information can be beneficial in improving traffic operations. Many traffic management centers (TMCs) have integrated weather information into traffic operations. However, studies that provide comprehensive evaluations of how weather information will affect TMCs' operations have not been conducted. Thus, the main purpose of this study is to evaluate the impacts of weather information on TMC users through investigation of the Utah Department of Transportation's Weather Operations/RWIS Program.

The first step in this study was to conduct an extensive literature review on the impacts of adverse weather on traffic operations and safety. Following this, survey of traffic operations center (TOC) users was conducted to learn about the effects of the Weather Operations Program on five TOC divisions' operations. Specifically, the survey results were analyzed to discover how weather information was used by TOC users and what benefits the users can achieve.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

The purpose of this (Phase II) research study is to evaluate the impacts of Utah Department of Transportation's Weather Operations/Road Weather Information System Program on Traffic Operations Center (TOC)'s operations. Phase I of the evaluation focused on developing an internal business case for the Program's utility based on its effects on winter maintenance. Building on the success of Phase I, Phase II focused on TOC users such as the incident management team, traffic signal group, and traveler information personnel that could benefit from the Weather Program. Together, the analysis of tangible benefits in Phase I and intangible benefits in Phase II provided a complete picture of how the Program has benefited the agency and helped establish a nationwide prototype of the unique Program with stationed meteorologists that provide year-round and area-specific weather forecasts to various users. The first step in the study was to conduct an extensive literature review on the impacts of adverse weather on traffic operations and safety. Following this, TOC users were interviewed to learn about the effects of the Program on the operations of the different divisions within the Department. The Program's benefits were also analyzed. The findings and conclusions of this study are summarized below.

1) The literature review found that adverse weather had extensive impacts on traffic flow. The degree of impact depended upon many factors such as precipitation intensity, time of day, day of week, etc. The effects of weather on traffic flow are summarized in the following table.

Traffic Flow	Condition		Percent Reduction
Speed	Rain*	N/A	2~9
	Snow*	N/A	5~19
	Fog	N/A	7~12
Traffic Volume/ Demand	Snowfall amount: <1 in	Weekdays	7~17
		Weekends	19~31
	Snowfall amount: 1~3 in	Weekdays	11~25
		Weekends	30~41
	Snowfall amount: 3~6 in	Weekdays	18~34
		Weekends	39~47
Capacity	Rain	Trace rain	1~3
		Light rain	5~10
		Heavy rain	10~17
	Snow	Trace snow (<=0.05 in/h)	3~5
		Light snow (0.06~0.1 in/h)	5~10
		Moderate snow (0.11~0.5 in/h)	7~13
		Heavy snow (>0.5 in/h)	30
Travel Time	Peak period average	N/A	(Increase) >11
	Off-peak period average	N/A	(Increase) 3.5

* Reductions are higher with heavy rain/snow.

2) The literature review also found that adverse weather affected arterial operations by reducing speed, traffic volume, and saturation flow rate. Using simulations, studies were able to show that the performance of arterial operations could be improved by implementing weather-responsive signal timing plans, including a more than 10 percent reduction in travel time. Existing studies also showed that adverse weather increased traffic crash risks. A Canadian study revealed that urban crashes increased by 70 percent during precipitation.

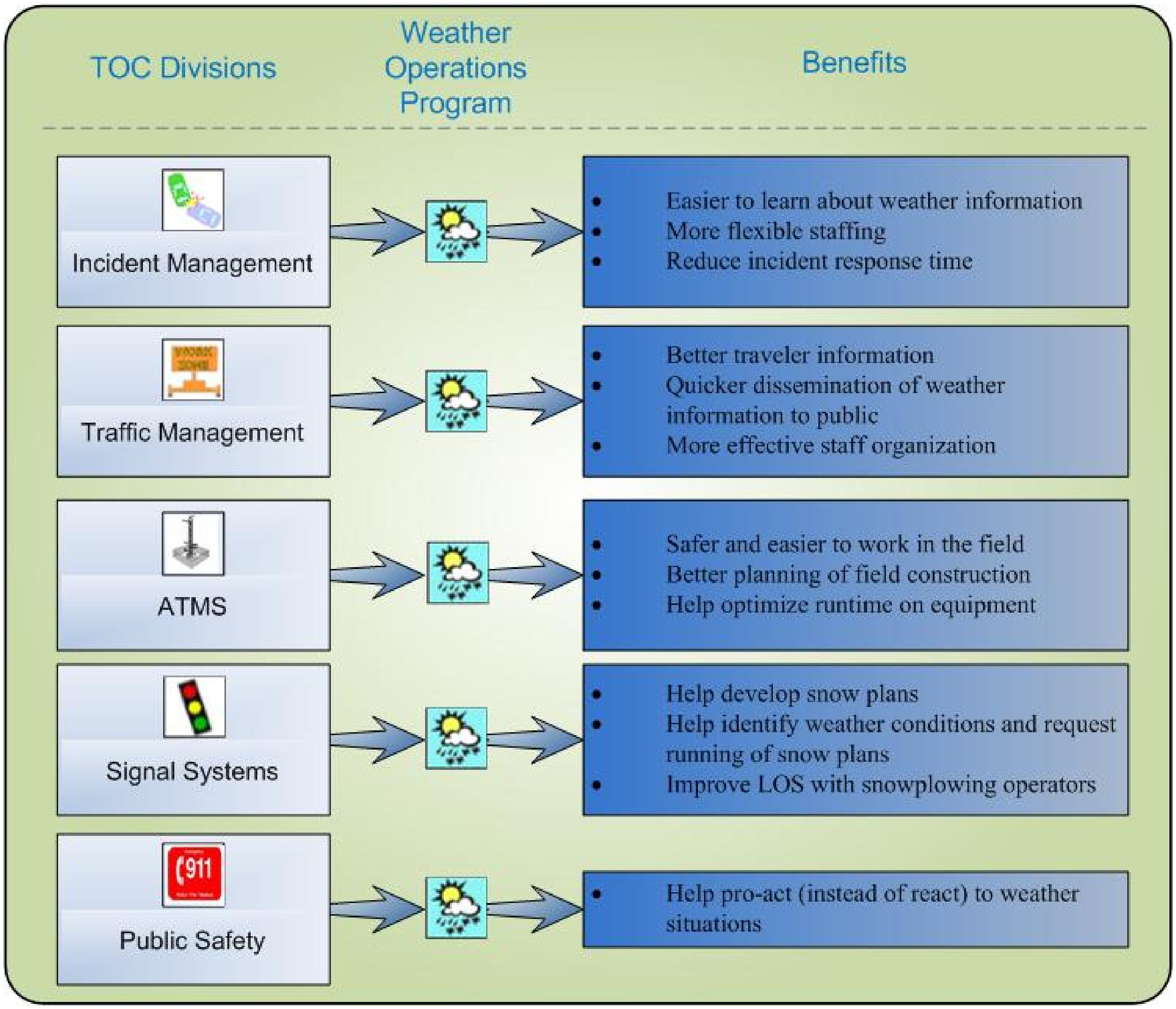
3) The interviews of TOC users found that the frequency of providing weather forecasts (twice per day, and more when weather situations coming in) met the needs of divisions. The station of meteorologists in the control room made it convenient for communications and update of weather information.

4) The weather elements and the time scales of weather forecasts that divisions were most interested in varied, as described in the following table. Long-term forecasts (>5 days) were less important to TOC users, as compared to other forecasts.

Division	Most Useful Weather Information	Priority of Different Time Scales of Weather Forecasts
Incident Management	Severe storms; Road hazard information	1st priority: Short-term (6~24 hrs)
Traffic Management	Road temperature; High winds on corridors; Weather inversions	1st priority: Medium-term (1~5 days) 2nd priority: Short-term
ATMS (Advanced Traffic Management System)	All information	Varied
Signal Systems	Severe storms	1st priority: Nowcasts (1~6 hrs) 2nd priority: Short-term
Public Safety	Snow storms	Priority decreases from nowcasts to long-term forecasts

5) The interviews with TOC users showed that the interviewees were very satisfied with the weather service provided by the Program. The divisions relied heavily on the Program for weather information. Most of the divisions did not use other weather information resources. All of the responses indicated that TOC users will continue or increase using weather forecasts.

6) The interviews revealed that the use of the Program's weather forecasts was beneficial for TOC users. The benefits to each of the five divisions are illustrated in the following figure. In general, the Program helps divisions organize their staffs more effectively so they can be better prepared for forthcoming weather situations.


TOC Divisions
Weather Operations Program
Benefits
Incident Management
• Easier to learn about weather information
• More flexible staffing
• Reduce incident response time
Traffic Management
• Better traveler information
• Quicker dissemination of weather information to public
• More effective staff organization
ATMS
• Safer and easier to work in the field
• Better planning of field construction
• Help optimize runtime on equipment
Signal Systems
• Help develop snow plans
• Help identify weather conditions and request running of snow plans
• Improve LOS with snowplowing operators
Public Safety
• Help pro-act (instead of react) to weather situations

CHAPTER 1. INTRODUCTION

The transportation community has been aware of the impacts of adverse weather on the roadway system and that the use of weather information can be beneficial in improving transportation operations. However, weather products are generally insufficient for transportation operations. For this reason, transportation agencies have been using customized weather information and integrating it into transportation operations, which is referred to as "*weather integration*"[1]. By providing Traffic Management Center (TMC) personnel with accurate and timely weather and road condition information, weather integration "*supports TMCs' ability to manage traffic, dispatch maintenance forces, and address weather-related emergencies*" [1].

Although many TMCs have integrated weather information for various purposes, studies that provide comprehensive evaluations of how weather information will affect TMC operations have not been conducted. In light of this lack of investigation, this research aims to evaluate the impacts of weather information on TMC users through a case study of the Utah Department of Transportation (UDOT) Weather Operations/Road Weather Information System (RWIS) Program (hereafter referred to as "the Program"). The following section provides some background information about the Program.

1.1 Weather Operations/RWIS Program

The Program was established in the 1990s and used Northwest WeatherNet (http://www.nw-weathernet.com/), based in Seattle, Washington, to provide forecasts. WeatherNet was chosen over National Weather Service (NWS: http://www.nws.noaa.gov/) forecasts as the NWS forecasts have a general safety focus (e.g., flood, fire, hurricanes) and UDOT was exploring operations pertinent to roads. The weather service started in UDOT's Region 2 and then became statewide for the 2002 Winter Olympics. The next year, during the winter season of 2002–03, the Program employed full-time meteorologists stationed in UDOT's TOC. The Program builds expert opinion (consensus), intuition, and science into the forecasts and provides site-specific forecasts that are deterministic and associated with a specific time frame.

Established under the TOC's Traffic Management Division, the Program has two main components. First, the Weather Operations component features four staff meteorologists stationed in the TOC to provide year-round weather support. Second, the Program has an Intelligent Transportation System (ITS) component, which manages 70 RWIS stations and expert systems such as bridge spray systems, high wind alerts, and fog warnings.

The Program provides various services to UDOT personnel (see Figure 1) including:

- forensic meteorology services (e.g., risk management, GRAMMA requests);
- services to Federal Highway Administration (FHWA) programs (e.g., Maintenance Decision Support System (MDSS), *Clarus* Initiative);
- forecasting services to UDOT maintenance, construction, and TOC personnel;
- planning and operations of RWIS; and
- RWIS and weather training courses.

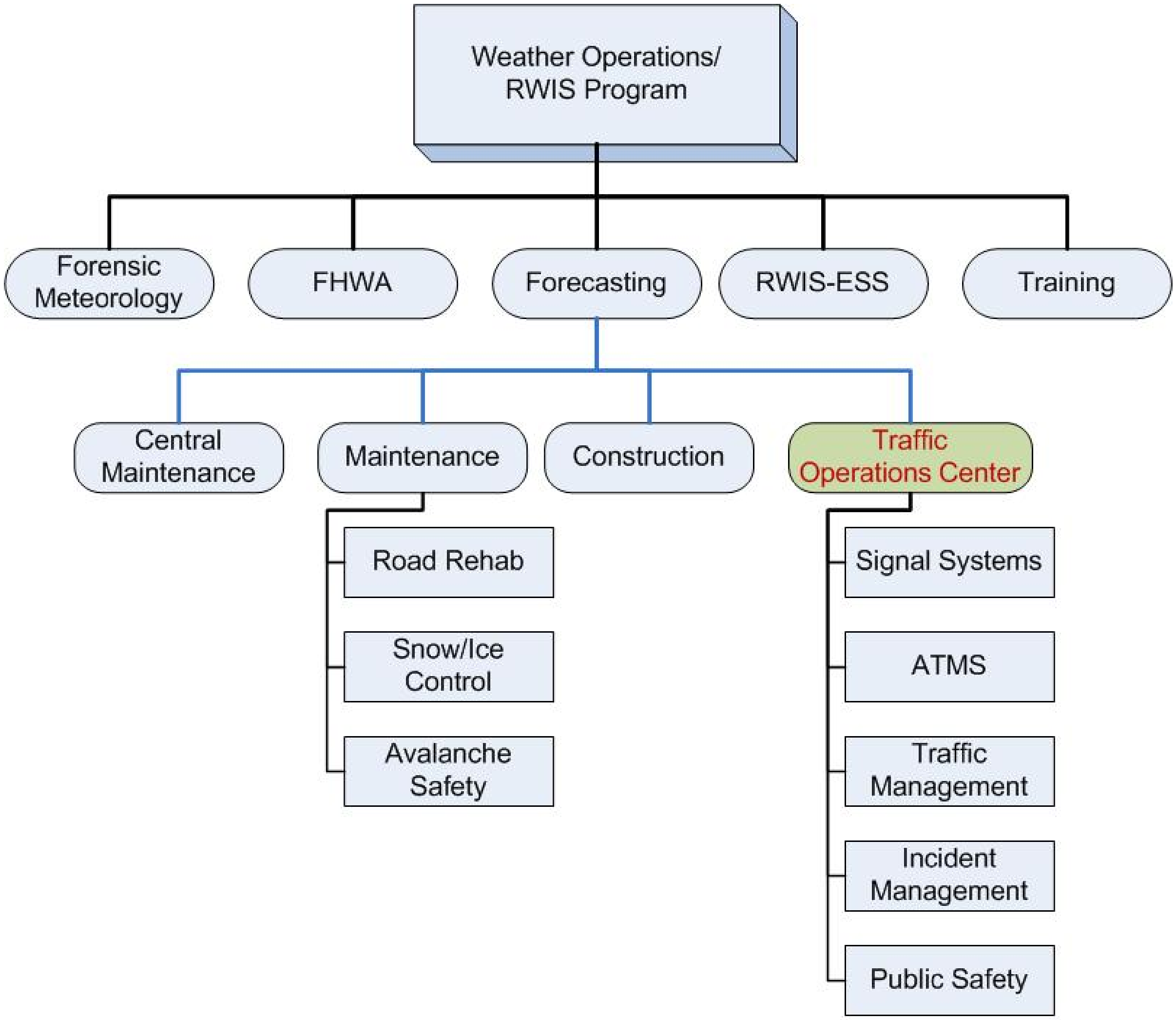


Figure 1: Organizational Chart of the Program's Weather Services

The Program provides the Office of Central Maintenance with year-round, long-term weather forecasts that are mainly used for planning of materials, staffing, and equipment. It provides pre-storm, during-storm, and post-storm weather forecasts to the maintenance managers, area supervisors, and local garages. It also provides forecast services for road rehabilitation and avalanche safety. Construction engineers and contractors receive weather forecasts for new construction and renovation projects.

A recent research study was conducted to estimate the cost-effectiveness of the Program on winter maintenance costs [2].The study estimated the value and additional saving potential of the UDOT weather service to be 11–25 percent and 4–10 percent of the UDOT winter maintenance costs, which include the costs of labor and materials. Based on the Program's cost, the benefit–cost ratio was calculated at over 11:1.

In addition to maintenance and construction, the Program provides customized weather forecasts to TOC divisions including signal systems, ATMS, Incident Management Team (IMT), traffic management, and Department of Public Safety (DPS).

The Program issues weather forecasts to the divisions twice a day (2 a.m. and 2 p.m.) or as there are critical changes in the forecast. The information sent in the morning includes weather forecasts for up to 36 hours (today and tomorrow) and afternoon forecasts are for 24 hours. The customized forecast information is disseminated through e-mail and includes weather forecasts for the six regions of the state (Region1, Region 2, Region 3, Cedar District, Richfield District, and Price District). An example of the morning forecast report for Region 2 is presented in Appendix A. The report includes a discussion of regional weather, the region extended forecast, and road forecasts for different areas in this region.

1.2 Organization of this Report

The rest of this report is organized as follows. A literature review on the impacts of adverse weather on traffic operations and safety is presented in CHAPTER 2. This section focuses on weather impacts on road users. The evaluation of the Program on TOC users is presented in CHAPTER 3. Finally, CHAPTER 4 summarizes the findings of this study.

CHAPTER 2. LITERATURE REVIEW: WEATHER EFFECTS ON TRAFFIC OPERATIONS

Weather has broad and significant effects on the roadway system [3]. Adverse weather such as rain and snow can reduce pavement friction and visibility distance, impairing the ability of drivers to operate their vehicles safely, reducing roadway capacity and significantly affecting system efficiency. In addition, many motor vehicle crashes occur due to weather events (e.g., rain, snow, sleet, fog, wet pavement, snowy/slushy pavement or icy pavement). The general impacts of weather events on roadways and traffic operations are summarized in Table 1 [4].

Table 1: Weather Impacts on the Roadway System

Weather Events	Impacts on Roadways	Impacts on Traffic
Rain, snow, sleet, hail and flooding	• Reduced visibility • Reduced pavement friction • Lane obstruction and submersion • Reduced vehicle performance • Infrastructure damage	• Reduced roadway capacity • Reduced speeds and increased delay • Increased speed variability • Increased accident risk • Road/bridge restriction and closures
High winds	• Reduced visibility due to blowing snow/dust • Lane obstruction due to wind-blown debris and drifting snow • Reduced vehicle performance	• Increased delay • Reduced traffic speeds • Road/bridge restrictions and closures
Fog, smog, and smoke	• Reduced visibility	• Reduced speeds and increased delay • Increased speed variability • Increased accident risk • Road/bridge restrictions and closures
Lightning, and extreme temperatures	• Infrastructure damage	• Traffic control device failure • Loss of power/ communications services

(Source: [4])

Many studies have been conducted to evaluate the effects of weather events on the transportation system. This chapter synthesizes those studies that were to evaluate/quantify the impacts of weather on traffic operations and traffic safety. Specifically, weather impacts on freeway traffic flow, arterial operations and safety are reviewed. As the majority of previous studies have focused on freeway traffic flow characteristics, weather impacts on speed, traffic volume, capacity, and travel time/delay were reviewed, respectively.

2.1 Speed

The impacts of weather events on traffic flow have been investigated for decades. A 1977 FHWA study revealed that speeds on interstate highways decreased under inclement weather conditions [5]. The percentage of speed reductions varied with pavement conditions, as described in the following table. Speeds were reduced as much as 42 percent when the pavement condition was "snowing and packed."

Table 2: Speed Reductions in Inclement Weather

Pavement Condition	Speed Reduction (%)
Dry	0
Wet	0
Wet and snowing	13
Wet and slushy	22
Slushy in wheel paths	30
Snowy and sticking	35
Snowing and packed	42

(Source: [5])

Referenced in the Highway Capacity Manual (HCM) 2000 [6], two studies found that speeds were affected by rain, snow, and fog events [7,8]. In addition, wet pavement did not affect speed until visibility was limited, with light rain having slight effects and heavy rain having noticeable effects on speeds. For snow, the influences depended upon the quantity or rate of snowfall, with light snow having minimal effects and heavy snow having large effects. Based on data collected from a freeway traffic management system, Ibrahim and Hall [8] quantified speed reductions as a result of rain and snow events (see Table 3).

Table 3: Speed Reductions by Rain and Snow

<table>
<tr><th colspan="2">Weather Events</th><th>Speed Reduction</th></tr>
<tr><td rowspan="2">Rain</td><td>Light rain</td><td>1.2 mi/h (free-flow speeds)
10% at a flow rate of 2,400 veh/h</td></tr>
<tr><td>Heavy rain</td><td>3 to 4 mi/h (free-flow speeds)
16% at a flow rate of 2,400 veh/h</td></tr>
<tr><td rowspan="2">Snow</td><td>Light snow</td><td>0.6 mi/h (free-flow speeds)</td></tr>
<tr><td>Heavy snow</td><td>38%</td></tr>
</table>

(Source: [8])

A recent FHWA study [9] that used data from Minneapolis/St. Paul, Minnesota, and Baltimore, Maryland, found that free-flow speed reductions were 2-3.6 percent (light rain: <0.01 cm/h), 6-9 percent (rain: 1.6 cm/h), 5-16 percent (light snow: <0.01 cm/h), and 5–19 percent (snow: 0.3 cm/h); speed reductions at capacity were higher than those at free-flow speeds, with corresponding reductions of 8-10 percent (light rain), 8-14 percent (rain), 5–16 percent (light snow), and 5–19 percent (snow). It is noted that the weather data for analysis were obtained from weather stations located at airports; the statistical analysis included the visibility variable and considered the interaction of visibility with precipitation rate.

An Aurora program research study used four years of freeway traffic data from in-pavement system detectors, and weather data from three Automated Surface Observing Systems (ASOS) and five RWIS sensors to quantify the impact of rain, snow, and pavement surface conditions on traffic flow [10]. The analysis results indicated that severe rain, snow, and low visibility caused the most significant reductions in capacities and operating speeds. Speed reductions were 4-7 percent (rain: >0.25 in/h), 11–15 percent (snow: > 0.5 in/h), and 10–12 percent (visibility: <0.25 mi). The speed reductions caused by rain and snow were lower than those in the HCM 2000. The impacts of rain, snow, and visibility on operating speeds are presented in the following table. The effects of wind speed and temperature on freeway speeds were also examined in this study, but those variables did not have significant effects (speed reductions of around 1–2 percent).

Table 4: Average Impact of Weather on Speed

Weather Variable	Intensity	Speed (mph)	Speed Reduction (%)
Rain	0	66.2	
	0~0.01 in/h	64.9	2
	0.01~0.25 in/h	63.6	4
	>0.25 in/h	62.2	6
Snow	0	66.2	
	<=0.05 in/h	63.4	4
	0.06~0.1 in/h	60.7	8
	0.11~0.5 in/h	59.9	9
	>0.5 in/h	57.2	13
Visibility	>1 mi	69.8	
	1~0.51 mi	65.1	7
	0.51~0.25 mi	64.8	7
	<0.25 mi	61.6	12

(Source: [10])

Liang et al. conducted a case study on the effects of environmental factors on vehicle speeds [11]. The case study location was a 160 km corridor on Interstate 84 (I-84) in southeast Idaho and northwest Utah. The sensors detected and measured traffic data, visibility data, and weather data. The Average Daily Traffic (ADT) for this highway section was 4,500 vehicles and the speed limit was 88.5 km/h (55 mph) during data collection. Fog and snow events were identified by using weather data. A multiple regression analysis found that the average speed reduction was

8.0 km/h (5 mph) during fog events and 19.2 km/h (12 mph) during snow events. Given that vehicle speeds were uniform with an average value of 103.5 km/h (64.7 mph), the percentages of speed reduction during fog and snow events were 8 and 18 percent, respectively. However, this regression analysis had a relatively low coefficient of correlation value and did not have clear definition of snow events. In a later study on the same highway, Kyte et al. [12] examined the effects of pavement conditions, visibility, and wind speeds on free-flow speed. Two-day (one good weather day and one bad day with low visibility) data were used for the analysis. It was found that the mean passenger-car speed was nearly 13 km/h (8.1 mph) lower for the bad day than the good day. The speed reduction was nearly 11 percent with a mean free-flow passenger-car speed of 121.8 km/h (76 mph) in the good day.

An international study was conducted in central Sweden during the winter of 1998–1999 to measure vehicle speed and flow in various weather conditions [13]. Traffic and weather data were measured at five road sites and aggregated into hourly values. These sites had low ADT (< 3,500 vehicles), with speed limits from 70-110 km/h (43.8-68.8 mph). The analysis of speed and flow in various pavement conditions took into account daily, weekly, and seasonal variations. It was found that the average speed reduction was 1 km/h (moisture pavement), 2 km/h (wet pavement), 4 km/h (hoarfrost), 5 km/h (black ice), 12 km/h (hard snow), 10 km/h (soft snow), and 11 km/h (slushy pavement).

In some recent studies [14,15], a series of speed adjustment factors were developed so that travel time and vehicle delay could be quantified to evaluate the benefits associated with the implementation of MDSS. The pavement conditions and their corresponding speed adjustment factors are presented in Table 5. These factors were developed based on existing studies that used RWIS data to identify roadway environments. In this table, “1” means no speed reduction and “0.96” corresponds to 4 percent of speed reduction.

Table 5: Speed Adjustment Factors

Pavement Condition	Factor
Dry	1
Wet	0.96
Chemically Wet	0.96
Damp	1
Lightly Slushy	0.9
Slushy	0.87
Deep Slushy	0.84
Dusting of Snow	0.96
Frost	0.94
Lightly Icy	0.94
Icy	0.85
Very icy	0.83
Lightly Snowcovered	0.89
Snowcovered	0.84

Based on the studies mentioned above, it is generally accepted that rain, snow, and fog (visibility distance) affect free-flow speeds. For rain and snow, the degree to which free-flow speeds are reduced depends on the intensity of precipitation (or precipitation rate). Heavier rain or snow has more effects on vehicle speeds than light rain/snow, due in part to the decreased visibility distances. However, it is difficult to summarize these effects because some studies used pavement conditions to quantify the effects, while others used weather variables. Also, the definition of the intensity of snow/rain/visibility is not uniform.

2.2 Traffic Volume/Demand

When adverse weather is coming in, people may postpone or even cancel their trip plans; some people change their modes of transportation, e.g., from passenger vehicles to transit. Thus, adverse weather affects traffic demand on the transportation system. Studies have shown that adverse weather reduced traffic demand on freeways and highways [e.g., 8,16,17,18].

A study by Hanbali and Kuemmel [16] was conducted to measure the effects of snowstorms on traffic volume on freeways and highways in the urban areas of Illinois, Minnesota, New York, and Wisconsin. The researchers collected traffic volume and weather data from 11 locations in these states for the first three months of 1991. Traffic volume reductions were calculated for different ranges of snowfall, ADT, roadway type, time of day, and day of the week. They found that the reductions in traffic volume varied with the categories of winter event; snowfall had a positive effect on volume reduction. However, the reduction was smaller during peak travel hours and weekdays, as shown in the following table.

Table 6: Traffic Volume/Capacity Reduction

Total Snowfall	Weekdays (%) (Range of Reduction)	Weekends (%) (Range of Reduction)
<25 mm	7~17	19–31
25~75 mm	11~25	30–41
75~150 mm	18~34	39–47

(Source: [16])

Knapp and Smithson investigated volume reductions due to snow events on interstate highways (I-35, I-80, I-235, and I-380) in Iowa [18]. Weather data from seven RWIS stations, hourly traffic flow data from Automatic Traffic Recorders (ATRs), and snowfall data from the Iowa Department of Agriculture and Land Stewardship (IDALS)/National Weather Service were collected for analysis. Winter storm events of four or more hours in duration and that had a snowfall intensity of 0.51 cm/h (0.20 in/h) or more were identified and evaluated. Sixty-four winter storm events were finally defined and analyzed. The results showed that winter storm events generally decreased traffic volumes, but the impacts varied. The volume reductions in these sixty-four storm events ranged from 16 to 47 percent, with an average value of 29 percent.

A recent study on I-35 in Iowa also explored volume reductions [19]. Traffic counts from ATRs during a number of snowy days (snowfall >1 in) were extracted and analyzed. A strong correlation between traffic volume reduction and wind speed and visibility was found. On snowy days, a 20 percent volume reduction was found with good visibility and low wind speed, and 80 percent or more of traffic volume reductions were identified with poor visibility (< 0.25 mi) and high wind speed (as high as 40 mi/h). It was also found that during snow storms, commercial vehicles had a higher percentage (by as much as 38 to 70 percent) of the traffic stream. The study explained that although motorists were diverting trips, commercial vehicle operators were much less likely to divert trips due to adverse weather.

These studies show that traffic volume decreased with the presence of inclement weather conditions. The percentage of volume reduction during off-peak hours or weekends was higher than that during peak hours or weekdays. Also, snow storms had more impacts on passenger cars than commercial vehicles. Overall, the volume reductions ranged from 7 percent to nearly 50 percent.

2.3 Capacity

Studies on the impact of rain and snow events on highway capacity are reviewed here.

2.3.1 Rain

A study in 1970 in Houston, Texas, found that rain events reduced traffic capacity on an I-45 segment by 14-19 percent [20]. In addition, Ries [21] conducted a study on I-35W in Minneapolis, Minnesota, and found that even a trace of precipitation contributed to capacity reduction of 8 percent. However, the HCM 2000 reported that under light rain conditions, little effect was observed on capacity; for heavy rain, maximum flow rates were 14 to 15 percent lower than those under normal weather conditions [6,8]. The Aurora program research study [10] indicated that the average capacity reductions were 1~3 percent (trace rain), 5~10 percent (light rain), and 10~17 percent (heavy rain). The FHWA study reported that capacity reductions remained constant (10~11 percent) and were not affected by rain intensity in the range of 0 to 1.7 cm/h (0 to 0.67 in/h) [9].

In conclusion, existing studies show that trace and light rain events do not have significant effects on capacity, while heavy rain events do affect capacity (10-17 percent reduction).

2.3.2 Snow

The HCM 2000 indicated that 5-10 percent reduction in capacity could be caused by light snow (0.06-0.1 in/h); trace (<=0.05 in/h) and moderate snow (0.11-0.5 in/h) caused 3-5 percent and 7-13 percent of capacity reductions. Heavy snow (more than 0.5 in/h) reduced capacity as much as 30 percent [6,8]. The Aurora program study [10] showed that heavy snow produced a similar reduction (19-28 percent) in capacity as that reported in the HCM 2000. The study by Ries [21] revealed that for every additional 0.25 cm/h (0.01 in/h) (water equivalent) of snow, there was a 2.8 percent reduction in capacity. The FHWA study found that light snow (0.01 cm/h) produced capacity reductions in the range of 12-20 percent and the reductions were not affected by snow intensity [9].

These studies indicated that snow had more impacts on capacity reductions than rain. Also, the impact of heavy snow on capacity reduction was in the range of 19-30 percent; trace, light and moderate snow events had less effects.

It is worth noting that the Aurora program study [10] also addressed the impacts of fog events and winds on capacity reduction: lower visibility (fog events) caused 10-12 percent of capacity reductions, while winds did not show a significant effect on capacity.

2.4 Travel Time/Delay

It was estimated that major events of fog, snow and ice combined to cause an estimated 0.5 billion vehicle–hours (0.9 billion person–hours) of delay on freeways and principal arterials in 1999 [22]. The study also indicated that snow was the most significant weather factor, accounting for 90 percent of the estimated delay. In 2006, the U.S. DOT reported adverse weather conditions of snow, ice, and fog contributed to 15 percent of all transportation system congestion [23].

A study conducted in Washington, D.C., sought to quantify the amount of travel time imposed upon drivers due to inclement weather [24]. Thirty-three bidirectional roadway segments in the metropolitan area were selected for analysis, with 18 of them freeway segments (472.4 mi) and 15 arterial routes (239.4 mi). Travel time data were extracted from archived information from the SmarTraveler web site (www.SmarTraveler.com). Travel time data were archived at approximately five-minute intervals. Hours of travel time data collection were from 6:30 a.m. to 6:30 p.m. (Monday through Friday) between December 6, 1999, and May 31, 2001. Archived hourly observations from ASOS were obtained from the National Climatic Data Center (NCDC). The weather elements included air temperature, dew point, wind speed and direction, and precipitation amount. The processed travel time and weather data were then combined for further regression analysis.

The analysis found that across all of the 33 roadways, the average regional increase in travel time due to adverse weather was 14 percent, which corresponded to 2.2-min delay on a 17-min trip. Regression results suggested a 13 percent increase in travel time due to an array of weather attributes (visibility, wind, and precipitation).

As indicated by the authors, the greatest shortcomings in this analysis were "*the absence of information on other variables affecting travel time beyond weather, the absence of roadway segment specific weather variables, and the qualitative nature of the travel time data,*" which resulted in meaningless outcomes of regression analysis of weather impacts during peak periods. Thus, the research team used a second method with the intent of using higher resolution (both spatially and temporally) weather data (radar data) to better approximate roadway conditions. Radar data were collected and correlated to road segments by using Geometric Information System (GIS). A method of *means analysis* was used to quantify the increase of travel time due to the effects of adverse weather. It was found that the average impact of precipitation on peak-period traffic was an increase in travel time of at least 11 percent. In addition, precipitation only caused a 3.5 percent increase in travel time during off-peak periods. Despite a wide range of roadways covered, this study did not separate the impacts of weather on travel time for freeway segments and arterial routes.

2.5 Arterial Operations

Inclement weather affected arterial operations by changing driver behavior and impairing the effectiveness of traffic signal timing plans [25]. A study in the United Kingdom investigated weather impacts on adaptive traffic signal systems in four urban areas [26]. Traffic flow data under dry and wet pavement conditions between March and November 1991 were obtained and analyzed. The results showed that under wet pavement conditions, saturation flow rate decreased by 6 percent and traffic delay increased by an average value of 11 percent. It was also concluded that increased congestion was due in part to the modified driver behavior and reduced vehicular performance.

In 1995, an Anchorage study [27] examined a traffic signal network (including five arterials with 24 signals) with the intent of determining whether arterial signal operations could be improved during the winter season. The study observed major street through movements, major street left-turning movements, minor street through movements, and upgrades (> 2 percent); the study also investigated signal timing plan parameters during summer, winter, and extreme conditions. It was concluded that the saturation flow rates in summer timing plans were reduced by 11~15 percent in the winter. Moreover, it was found that average winter traffic speeds during peak periods were 16 percent lower than summer design speeds.

During the winter season of 1998–99, Maki [28] examined weather impacts on a three-mile arterial that had five traffic signals in Minneapolis/St. Paul, Minnesota. It was found that in inclement weather, traffic volumes were 15~20 percent lower during peak periods and 15~30 percent lower during the peak hour; reductions in saturation flow rate was 11 percent; start-up delay was increased by 50 percent; and a 40 percent speed reduction (from 44 mph to 26 mph) was also identified.

During the winter of 1999–2000, Perrin et al. investigated weather impacts on two intersections in Salt Lake City, Utah [29,30]. Fourteen days of data, including inclement weather speed, flow rate, and start-up delay, were collected. They found that start-up delay on wet pavement and snowy pavement was 5 and 23 percent higher, respectively, than that on dry pavement. The reductions in free-flow speed and saturation flow are described in Table 7.

Table 7: Weather Impacts on Arterial Operations in Utah

Road Weather Conditions	Free-Flow Speed Reduction (%)	Saturation Flow Rate Reduction (%)
Dry	0	0
Wet	10	6
Wet & Snowing	13	11
Wet & Slushy	25	18
Wheel Path Slush	30	18
Snowy & Sticking	N/A	20

(Source: [29])

During the winter of 2002–2003, Seli et al. [31] conducted a study to assess the impact of inclement weather on traffic flow parameters at signalized intersections in northern New England. A signalized intersection in Burlington, Vermont, was selected and more than 30 hours of videotaped data were collected over a period of three months. Weather and road surface conditions were analyzed and categorized into six classes. As shown in Table 8, the authors found that saturation flow rate was reduced by a range of 2-21 percent, depending on road weather conditions.

Table 8: Weather Impacts on Saturation Flow Rate in Vermont

Road Weather Conditions	Saturation Flow Rate Reduction	
	Eastbound Approach (at grade) (%)	Westbound Approach (uphill grade) (%)
Dry	0	0
Wet	3	2
Wet & Snowing	7	4
Wet & Slushy	7	15
Wheel Path Slush	N/A	21
Snowy & Sticking	16	16

(Source: [31])

Pasino and Goodwin summarized weather impacts on arterial operations based on seven studies [25], as described in the following table.

Table 9: Summary of Weather Impacts on Arterial Operations

Study Dates and Areas	Facilities	Reductions (%)				Increases (%)	
		Average Speed	Free-Flow Speed	Average Volume	Sat. Flow Rate	Travel Time Delay	Start-Up Delay
1991 U.K.	4 urban networks				6	11	
1995 AK	Rural network with 5 arterials, 24 intersections	16			11~15		
1999 MN	Arterial with 5 intersections	40		15~30	11		50
2000 UT	2 intersections		10~30		6~20	50	5~23
2001 D.C.	Urban network with 15 arterials					12~48	
2003 VT	Intersection, 1 uphill approach				2~21		
2003 Simul.	Arterial with 4 intersections	36					20

(Source: [25])

Data show that weather-related average speed reductions were between 16 and 40 percent; free-flow speed reductions ranged between 10 and 30 percent; traffic volumes were reduced by 15-30 percent; saturation flow rate were reduced by 2~21 percent; traffic delay increased by 11-50 percent, and start-up delay was 5-50 percent higher.

Due to the impacts of adverse weather on arterial operations, weather-responsive signal timing plans have been implemented in some cities such as Charlotte, North Carolina, and Clearwater, Florida [25]. Studies that used simulation methods have shown that weather-responsive signal timing plans could improve arterial mobility, as is illustrated in the following table. The simulation studies found that the reductions were 7~23 percent in average delay, 13~18 percent in traffic delay, and 4~9 percent in vehicle stops. The average speed was improved by 3~12 percent.

Table 10: Summary of Simulation Studies on Weather-Responsive Signal Timing

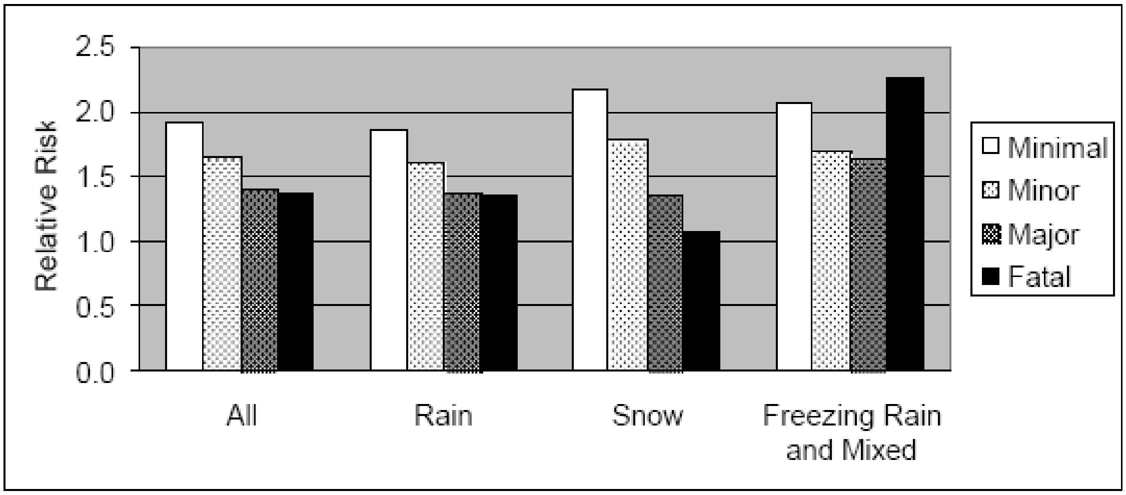
Study Dates And Areas	Facilities Simulated	Reductions (%)				Increase (%)
		Signal Delay/ Vehicle	Average Delay	Travel Time/ Delay	Vehicle Stops	Average Speed
1995 AK	Rural network with 5 arterials, 24 intersections		23	13		12
1999 MN	Arterial with 5 intersections	8			6	
2000 UT	Arterial with 9 intersections			18	9	
2003 VT	Arterial with 10 intersections		7		4	3

(Source: [25])

2.6 Safety

Weather-related crashes injure 690,000 people and kill 7,400 people each year in the United States; these crashes contribute to more than 24 percent of all vehicle crashes [32]. Studies in North America indicated that the impacts of adverse weather increased crash risk. Andrey et al. [33] conducted a national study on increased driving risks associated with inclement weather in Canada. To do this, weather data and collision records for 27 cities over a 17-year period (1984~2000) were collected. Weather data were gathered from the climate archive of the Meteorological Service of Canada; injury and fatal crash data were obtained from Transport Canada's national collision database.

For each of the 27 cities, the researcher compiled the weather data and summarized the frequency of different weather events. Following this, the effect of weather on casualty rate was explored. The analysis results are illustrated in Figure 2.



(Source: [33])

Figure 2: Relative Risks for Different Types of Precipitation

As shown in the leftmost columns, for all precipitation, the relative risks for minimal injury, minor injury, major injury, and fatal injury were 1.9, 1.6, 1.4, and 1.4, respectively. It is obvious that crash risks increased due to precipitation. The study also combined the information of different levels of injury severity and reported a relative risk ratio of 1.7, which means that across the nation, urban crashes increased by 70 percent during precipitation [33].

From the figure above, it can be also seen that the risk ratios of "rain" were close to those of "all precipitation"; snow increased crash risk by approximate 120, 80, 40, and 40 percent for minimal, minor, major, and fatal injuries, respectively; for "freezing rain and mixed with snow," the risks were approximate 110, 70, 60, and 120 percent higher than normal conditions.

Another crash risk investigation in adverse road weather conditions was conducted in the United States by Pisano et al. [32]. Eleven years of police-reported crash data from 1995 to 2005 were obtained from the National Highway Traffic Safety Administration (NHTSA) databases—the Fatality Analysis Reporting System (FARS) that contains data on all fatal traffic crashes on U.S. public roads, and the General Estimates System (GES) that provides estimates based on a nationally representative sample of police-reported crashes. The detailed information about weather-related crash statistics is shown in Figure 3. The major findings of this study can be summarized as follows [32]:

- Weather-related crash fatalities account for 17 percent of all traffic fatalities each year. And the values for injury and property-damage-only crashes are 22 and 25 percent, respectively.

- Most weather-related crashes happen on wet pavement and during rainfall, with 75 percent on wet pavement, 47 percent during rainfall, 15 percent during snow or sleet, 13 percent on icy pavement, 11 percent on snowy or slushy pavement, and 2 percent in the presence of fog.

Road Weather Conditions	WR* Crash Statistics: Annual Rates (Approximately)	Percentages	
Wet Pavement	1,170,000 crashes	18% of vehicle crashes	75% of WR crashes
	544,700 persons injured	17% of crash injuries	81% of WR crash injuries
	5,700 persons killed	13% of crash fatalities	77% of WR crash fatalities
Rain	739,200 crashes	12% of vehicle crashes	47% of WR crashes
	357,300 persons injured	11% of crash injuries	53% of WR crash injuries
	3,400 persons killed	8% of crash fatalities	47% of WR crash fatalities
Snow/Sleet	232,600 crashes	4% of vehicle crashes	15% of WR crashes
	75,700 persons injured	2% of crash injuries	11% of WR crash injuries
	900 persons killed	2% of crash fatalities	12% of WR crash fatalities
Icy Pavement	197,300 crashes	3% of vehicle crashes	13% of WR crashes
	67,300 persons injured	2% of crash injuries	10% of WR crash injuries
	700 persons killed	2% of crash fatalities	10% of WR crash fatalities
Snow/Slushy Pavement	168,400 crashes	3% of vehicle crashes	11% of WR crashes
	49,500 persons injured	2% of crash injuries	7% of WR crash injuries
	600 persons killed	2% of crash fatalities	9% of WR crash fatalities
Fog	38,700 crashes	1% of vehicle crashes	2% of WR crashes
	16,300 persons injured	1% of crash injuries	2% of WR crash injuries
	600 persons killed	2% of crash fatalities	9% of WR crash fatalities
WR	**1,561,400 crashes**	**24% of vehicle crashes**	
	673,200 persons injured	**22% of crash injuries**	
	7,400 persons killed	**17% of crash fatalities**	

*-WR means weather-related.

(Source: [32])

Figure 3: Weather-Related Crash Statistics (1995–2005, US)

2.7 Summary

In this chapter, the impacts of adverse weather on traffic flow and safety were identified through a comprehensive literature review. The bulk of studies collectively show that adverse weather can reduce operating speeds, traffic volume/demand, and capacity; increase travel time; and increase the risk of vehicle crashes.

Weather impacts on operating speeds vary with road and weather conditions. Studies revealed that speed reductions caused by rain range between 2 and 9 percent; the reductions by snow and fog were higher, with ranges of 5-19 percent (snow) and 7-12 percent (fog). Heavy rain and snow events as well as unfavorable pavement conditions could result in higher percentages of speed reduction.

Traffic volume/demand reductions due to adverse weather were higher during weekends or off-peak periods than during weekdays or peak periods. In addition, the reductions in passenger car volumes were higher than commercial vehicles. Overall, traffic volume reductions ranged from 7 percent to nearly 50 percent.

Capacity (or maximum flow rate) was also reduced under inclement weather conditions. Table 11 summarizes the reduction values associated with different weather conditions.

Table 11: Summary of Capacity Reductions by Adverse Weather

Weather Condition		Capacity (or Maximum Flow Rate) Reduction (%)
Rain	Trace	1~3
	Light rain	5~10
	Heavy rain	10~17
Snow	Trace	3~5
	Light snow	5~10
	Moderate snow	7~13
	Heavy snow	19~30
Fog		10~12

The increase of travel time due to precipitation was more than 11 percent during peak periods, and was approximately 3.5 percent during off-peak periods, according to a study done in the metropolitan area of Washington D.C.

For arterial operations, speed and volume were reduced by the presence of adverse weather; also, travel time as well as start-up delay was increased. These impacts were presented in Table 9. The use of weather-responsive signal timing was found to be an effective measure to improve the mobility of arterial operations during adverse weather.

A national study in the United States found that weather-related crashes contribute to 24 percent of all vehicle crashes each year. Also, a nationwide study in Canada showed that the relative risks of minimal, minor, major, and fatal injuries during inclement weather conditions were 90, 60, 40, and 40 percent higher, respectively, than those during normal weather conditions.

CHAPTER 3. EFFECTS OF THE WEATHER OPERATIONS PROGRAM ON TOC

The previous chapter reviewed and summarized the effects of adverse weather on road users. Implied in the results of the studies on those effects is that the use of timely and accurate weather information can help improve traffic safety and mobility during adverse weather. The use of weather information also brings benefits to transportation agencies. Studies showed that the use of weather information reduced winter maintenance costs (including materials, staffing, and equipment usage costs) [2,34].

The benefits to road users of using weather information, however, largely depend upon the effectiveness of transportation agencies' responses to weather situations. Timely and efficient reactions can help travelers be better prepared for the situations and improve traffic safety. For this reason, it is important to know how weather information is integrated into traffic operations and what benefits can be achieved. Thus, this chapter focuses on the impacts of the Program on TOC users, and investigates how the Program affects their daily activities. Telephone interviews of TOC personnel were conducted to learn about the effects. A list of questions was developed for the interviews. Realizing that TOC consists of different divisions that take on different tasks, some specific questions were customized for each division in accordance with the division's operational procedures and responsibilities. Questions for the different divisions are presented in Appendix B. The interviews were conducted to mainly answer the following questions:

- What weather information from in-house meteorologists is used by TOC personnel?
- How weather information is applied to different TOC divisions?
- How frequently is weather information used?
- What are the effects/benefits of using weather forecasts from the Program?
- What is the tendency of using weather information in the future?

The results of phone interviews with TOC users are presented in the following subsections. The benefits of the Program to these users are also summarized.

3.1 Incident Management Team (IMT)

The daily activities of the IMT mainly include patrolling major highways, looking for stranded people on the roadway, and assisting the Utah Highway Patrol (UHP). The normal hours of operation are between 6:30 a.m. and 7:00 p.m.

The division personnel received weather forecasts from the Program at least once per day. If there was a weather situation, they received forecasts up to 10 times per day. The interviewee said the division usually didn't call the Program for weather information. Instead, the staff of the Program sent email to the division as soon as changing weather conditions were indentified. The division relied on the Program for weather information and didn't use other weather resources. The Program has made it easier for the division to know about current and future weather situations instead of having to observe the weather themselves.

The interviewee is responsible for receiving and reviewing weather information every day. When there are no significant weather events forecasts, then just knowing that information is valuable. Otherwise, the interviewee will inform the crew about the situation, and the crew will make preparations to handle weather-related problems.

The division is most interested in severe storms and road hazard information. Short-term forecasts (6–24 hrs) are the first priority for this division, while medium-term and long-term forecasts are less important.

The interviewee said that the IMT had a high level of trust in the Program because short-term forecasts were very accurate. It was also indicated that the division achieved benefits by using weather forecasts from the Program. The benefits can be summarized as follows:

- There is no need for the division to gather weather information through other resources. Having a single source makes it easier to keep track of weather developments.
- The crew doesn't have to be on call all the time. The division is more flexible in terms of staffing.
- Incident response times have improved during weather events with the use of weather forecasts. The crew will be called out before the weather event comes in, and it can be on the road before roadway conditions worsen. Thus, they can be on the job faster and be better positioned for developing situations.

3.2 Traffic Management Division

The traffic management division in the TOC is responsible for monitoring traffic cameras (in the control room), watching traffic data (speed, volume, and density) from loop detectors, disseminating traveler information (on variable message signs (VMS), 511, web site, etc.), and implementing new technologies (e.g., radar units). The hours of operation in this division vary: it can be 24 hours a day in the control room at its busiest in the winter, but the primary focus is from 5:00 a.m. to 11:00 p.m. with two to three operators on duty. Nearby ski resorts begin drawing traffic early in the morning, so the division needs to have staff on duty to receive weather information as early as possible. One person is present in the division between 11:00 p.m. and 5:00 a.m. in the morning.

A traffic operations engineer from this division was interviewed. The interviewee indicated that the division relied heavily on weather forecasts. The Program provides forecasts for road weather conditions such as slushy, freezing rain, and snow. On a normal day, there are two to three staff on duty but the number will increase to 10 and sometimes 12 when there is a storm event. Each person is assigned specific tasks, such as updating the web site and 511. Everybody in the building has other duties and they will be on call and supplement the control room when there is a weather situation.

The division receives weather reports twice per day. When a storm is forecast, the division will typically have a weather briefing, usually two days in advance. The Program presents weather details to the division. Then the division will make judgments about what the information means for traffic operations and how many personnel are necessary for response. The Program will inform the division when weather briefings are necessary.

The division did not use weather information from other resources as it relied heavily on information provided by the Program. The division works closely with weather people—the meteorologists of the Program are stationed in the control room. If traffic management engineers need details on a weather forecast, they just walk in and talk to the meteorologists. The Program will inform them what weather event will happen and what they should be concerned about. The division will then use that information to make decisions and respond to the weather event—e.g., providing or updating weather information in 511 messages.

The weather forecast elements that the division is most interested in include road temperatures, wind speeds on corridors, and weather inversions.[1] The division focuses primarily on medium-term forecasts (one to five days) to watch storms coming in. The second priority is short-term forecasts (6–24 hrs) to obtain the details when a storm is getting close. Nowcasts (1–6 hrs) are provided on a more ad hoc basis. Occasionally, traffic management engineers may speak to meteorologists directly to ask them about the latest news on storms.

Benefits of the Program to the traffic management division were identified through the interview. First, the quality of the information disseminated to the public is better when using weather forecasts from the Program. Second, the division can start disseminating information sooner and can present better quality information to the public concerning specific instructions regarding weather events. Third, the Program allows the division to organize itself in a more effective way during the winter season. The division needs to increase staffing during storms, which involves people changing their work tasks. The earlier the division has the weather information it needs to make those staffing decisions, the easier it is to schedule and prepare the appropriate staff.

The interviewee also indicated that the division was very satisfied with the quality of services provided by the Program. The division will continue to rely heavily on weather forecasts. The division is expanding the reporting functions on the Utah CommuterLink[2] (http://commuterlink.utah.gov/) to include forecasting information at key spots around the state, such as mountain passes and corridors with heavy traffic.

3.3 ATMS Division

The ATMS division is responsible for the maintenance of ATMS devices (e.g., VMS, HAR—Highway Advisory Radio, RWIS, TMS—Traffic Management Stations), maintenance of ramp meters, the maintenance of communication lines to field devices, and deployment of new

[1] Inversions occur when cold, dense air gets trapped against the mountains under a layer of warmer air. The denser air can collect pollutants and become hazy. In winter, when a low pressure layer covers Salt Lake City for a long period of time, air quality can degrade significantly. When the quality degrades to the point that the health department recommends people not go outside, UDOT uses variable message signs on freeways to disseminate the information (e.g., to limit driving, how long the situation will last).

[2] CommuterLink is a computer-controlled system designed to monitor and manage traffic flow on freeways and surface streets. System components include closed-circuit television (CCTV) cameras, electronic roadway signs (ERS), the 511 Travel Information Line, coordinated traffic signals, ramp meters, traffic speed and volume sensors, pavement sensors, and weather sensors.

equipment. The staffs in this division work in the field from 6 a.m. to 4:30 p.m. Monday through Friday.

The division receives weather forecasts from the Program twice per day by e-mail. The Program will call the division several times during adverse weather. In addition, the division usually calls the Program on a daily basis, and sometimes two or three times during a storm. If the division has a major project that requires good weather for a period of time (e.g., 10 hours to 3 days), the division will call the Program for advice about the best time or the best days to have the work done.

Weather forecasts provided by the Program have extensive applications in the division. Examples of the applications are described below.

- When the division's staffs are doing aerial work (e.g., replacing cameras or working on freeway lighting), they need to know about high wind warnings and lightning information in the area for safety reasons.
- When weather forecasts show warnings of a major snow storm, the division will check with chain-up signs to make sure that they are operational before the storm.
- Through the use of a portable weather station with camera in new construction sites, the Program will provide warnings to contractors when adverse weather is approaching.

The interviewee said that the division has in interest in all of the weather information provided by the Program. Also, there is not a fixed priority ranking for different time scales (from nowcasts to long-term forecasts) of weather forecasts. Priorities depend on the work that the division is taking on during a specific day or week. The division does not use other resources for weather information.

The interviewee in this division revealed that the use of weather forecasts has several benefits. First, it is safer and easier to work in the field when knowing about weather conditions. Second, it allows the division to plan field construction or new construction between bad weather days. Finally, it helps the division to optimize runtime on existing equipment.

3.4 Signal Systems Division

The signal systems division is responsible for the operation of 1,100 traffic signals and 45 ramp meters on UDOT intersections and freeways statewide. The division does not maintain the traffic signals and ramp meters, rather it operates and optimizes the signal timings. This work includes responding to traffic signal timing complaints, installing and fine-tuning new coordinating plans, optimizing signal timing parameters, managing the central system (e.g., i2TMS[3] and SCATS—Sydney Coordinated Adaptive Traffic System), and programming dilemma zone detection. In addition, the division changes signal coordination as needed for special events, incident management, and weather conditions. The division also installs new traffic signal controllers for upgrades and updates existing firmware for controllers already in the field. The normal hours of operation are from 7:00 a.m. to 6:00 p.m. Monday through Friday.

[3] A traffic signal system developed by Siemens.

Signal timing plans have been developed for Region 2 of the state to help with snow plowing and traffic flow during snowstorms and adverse weather. These weather-responsive timing plans are currently implemented for 22 routes (including nine in central business districts), as shown in Figure 4 [35]. For each route, a signal timing action set was created based on snowfall, day of week and time of day. Table 12 presents an example of an action set on Bangerter Highway from California Avenue to 9000 South. Three different signal coordination plans (action sets of 134, 135, and 136) are used for this route to balance northbound/southbound progression under severe weather conditions. This route runs special phase sequences (e.g., lead/lead as opposed to lead/lag phasing) to assist the snowplow operators in plowing.

General criteria are used when considering triggering the action sets. Action sets may be implemented if all of the following five conditions are met [30,35].

- Actions sets are requested by TOC meteorologists or shed supervisors;
- There is a significant reduction in travel speed due to weather (timing planes are generally designed for a 30 percent reduction in free-flow speed);
- Signals are coordinated at the time considered (signals may not be coordinated late at night);
- Delay-causing weather conditions will last at least 20 minutes; and
- Traffic is congested.

Once the action sets are implemented, the affected route should be monitored using closed-circuit television if possible. Also, action sets should remain active until snowplowing operations are complete, the next step in the schedule is reached, the adverse weather is no longer affecting traffic, or a request is made by a shed supervisor or TOC meteorologist to disable the sets.

Snow plans have been implemented during the winter season since 2003 in Region 2. For example, snow plans were run on the corridors 115 times in 2008. Most of them (110 times) were run in January, February, and December, and the rest were run in March and April. The frequency of running snow plans depends on winter weather severity and, thus, varies from year to year.

The signal systems division uses weather reports from the Program everyday, and it also uses the Utah CommuterLink to know about the most recent forecasts. When storms are coming in, the Program will work with traffic engineers in the division and inform them of the time and locations where the snow coordination plans need to be run. The division is most interested in knowing when the weather is bad enough to trigger the snow plans, the locations that storms will affect, and the time of day and duration of the event. Nowcasts (1–6 hrs) are of most importance for the division, followed by short-term forecasts (6–24 hrs). Medium-term and long-term forecasts are not necessary for the division's needs.

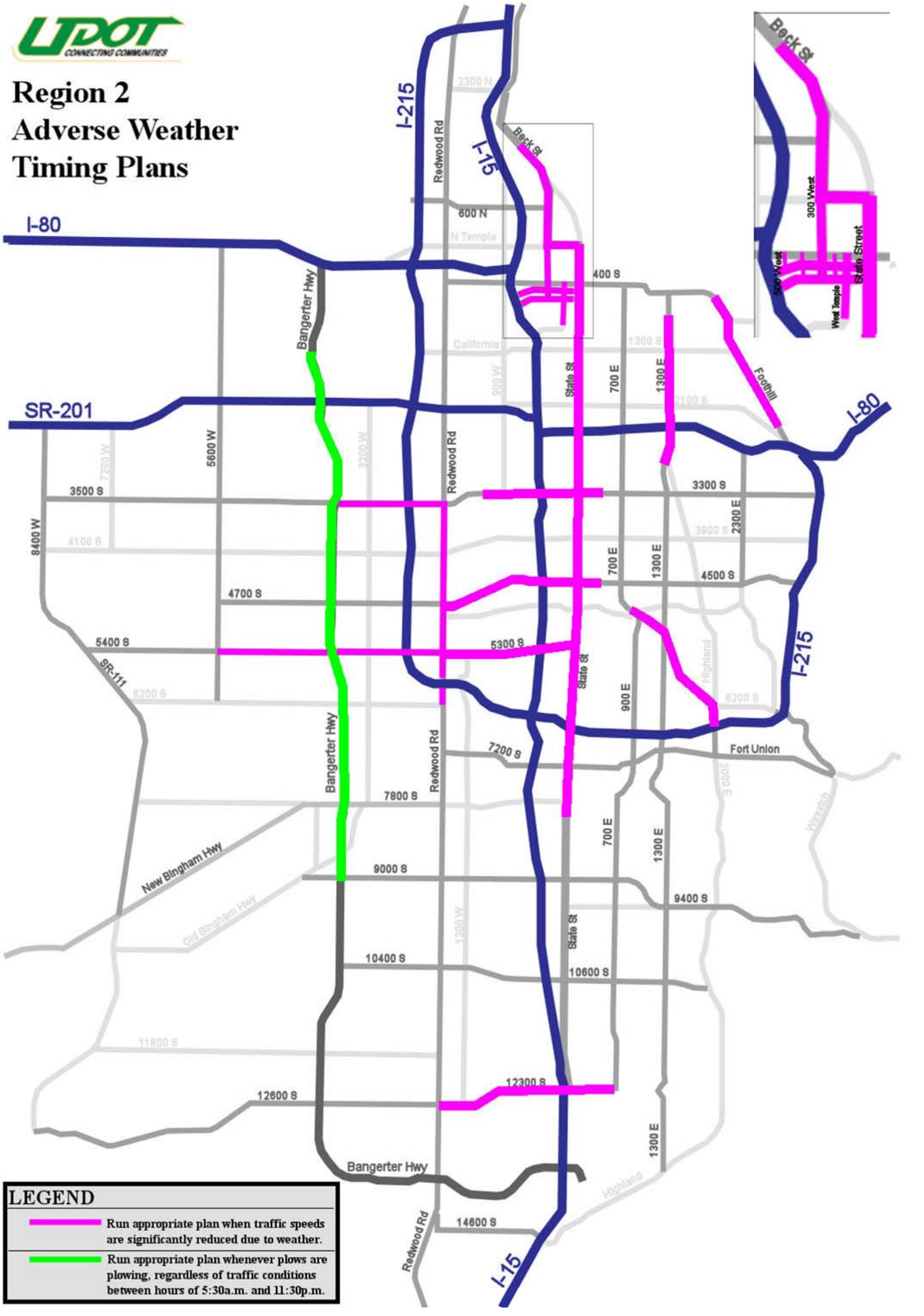


Figure 4: Routes with Snow Plans in Region 2, Utah

Table 12: Example of Signal Timing Action Set

Bangerter Highway, from California Avenue to 9000 South

Special Note: Run appropriate snow plan whenever plows are plowing, regardless of traffic conditions, between hours of 5:30 AM and 11:30 PM.

Snowfall	Day of Week	Time of Day	Action Set	Description
Moderate – Heavy	Saturday and Sunday	07:00 to 23:30	**SET:136**	Balanced N/S Progression, 150-s. cycle length
Moderate – Heavy	Monday thru Thursday	05:00 to 06:30	**SET:136**	Balanced N/S Progression, 150-s. cycle length
Moderate – Heavy	Monday thru Thursday	06:30 to 09:00	**SET:134**	Favors NB Progression, 150-s. cycle length
Moderate – Heavy	Monday thru Thursday	09:00 to 16:30	**SET:136**	Balanced N/S Progression, 150-s. cycle length
Moderate – Heavy	Monday thru Thursday	16:30 to 18:30	**SET:135**	Favors SB Progression, 150-s. cycle length
Moderate – Heavy	Monday thru Thursday	18:30 to 23:30	**SET:136**	Balanced N/S Progression, 150-s. cycle length
Moderate – Heavy	Friday	06:30 to 09:00	**SET:134**	Favors NB Progression, 150-s. cycle length
Moderate – Heavy	Friday	09:00 to 14:00	**SET:136**	Balanced N/S Progression, 150-s. cycle length
Moderate – Heavy	Friday	14:00 to 19:00	**SET:135**	Favors SB Progression, 150-s. cycle length
Moderate – Heavy	Friday	19:00 to 23:30	**SET:136**	Balanced N/S Progression, 150-s. cycle length

The interviewee from this division said they were very satisfied with the services provided by the Program. The Program helps the division in several ways. First, it helps develop snow plans. Secondly, the Program helps identify weather conditions and requests the implementation of action sets, as meteorologists have better knowledge of weather conditions. Finally, the Program helps improve the Level of Service with snowplowing operators—e.g., through the use of lead/lead phasing.

3.5 Department of Public Safety (DPS)

The DPS is a 911 dispatch center that is staffed 24 hours a day. The division receives weather reports twice a day and uses them extensively. The division also receives weather briefings (presented by the Program) on the days that weather might be adverse. Thus, the division rarely calls the Program for weather information because the feedback is daily and prompt. In addition to weather information provided by the Program, the division uses the Internet to check weather conditions, particularly during the winter.

The division will notify UHP of the weather conditions so it can deploy staff when necessary. Weather forecasts also allow the division to decide when to increase staffing to cover dispatch consoles and troopers in the field when adverse weather is approaching. Snow forecasts that will impact traffic are of most interest to the division. The importance of different forecast time scales decreases from nowcasts to short-term forecasts, medium-term forecasts, and long-term forecasts.

The interviewee said that the mobility and safety of the public is very important to the division. When traffic flow is impeded, prior knowledge of weather events allows them to pro-act instead of react to the situation, and the Program helps in this regard. The interviewee said the division relied more on the Program than other weather forecast resources and would continue using this service.

3.6 Summary of Benefits to TOC

The results of interviews found that the use of weather forecasts is beneficial to TOC divisions. The benefits to each division are summarized in the following table.

Table 13: Benefits of the Program

Division	Benefits
Incident Management	• Easier to learn about weather information • More flexible staffing • Reduce incident response time
Traffic Management	• Better traveler information • Quicker dissemination of weather information to public • More effective staff organization
ATMS	• Safer and easier to work in the field • Better planning of field construction • Help optimize runtime on equipment
Signal Systems	• Help develop snow plans • Help identify weather conditions and request running of snow plans • Improve LOS with snowplowing operators
Public Safety	• Help pro-act (instead of react) to weather situations

CHAPTER 4. FINDINGS AND CONCLUSIONS

The purpose of this research study is to evaluate the impacts of UDOT's Weather Operations Program on TOC. The researcher first conducted an extensive literature review on the impacts of adverse weather on traffic operations and safety. Then, interviews of TOC users were conducted to learn about the effects of the Program, including its benefits, on operations in the different divisions. The findings and conclusions of this study are summarized below.

1) The literature review found that adverse weather had extensive impacts on traffic flow. The degree of impact depended upon many factors such as precipitation intensity, time of day, day of week, etc. The effects of weather on traffic flow are summarized in the following table.

Table 14: Weather Impacts on Traffic Flow

Traffic Flow	Condition		Percent Reduction
Speed	Rain*	N/A	2~9
	Snow*	N/A	5~19
	Fog	N/A	7~12
Traffic Volume/ Demand	Snowfall amount: < 1 in	Weekdays	7~17
		Weekends	19~31
	Snowfall amount: 1~3 in	Weekdays	11~25
		Weekends	30~41
	Snowfall amount: 3~6 in	Weekdays	18~34
		Weekends	39~47
Capacity	Rain	Trace rain	1~3
		Light rain	5~10
		Heavy rain	10~17
	Snow	Trace snow (<= 0.05 in/h)	3~5
		Light snow (0.06~0.1 in/h)	5~10
		Moderate snow (0.11~0.5 in/h)	7~13
		Heavy snow (>0.5 in/h)	30
Travel Time	Peak period average	N/A	(Increase) >11
	Off-peak period average	N/A	(Increase) 3.5

* Reductions are higher with heavy rain/snow.

2) The literature review also found that adverse weather affected arterial operations by reducing speed, traffic volume, and saturation flow rate. Using simulations, studies were able to show that the performance of arterial operations could be improved by implementing weather-responsive signal timing plans, including a more than 10 percent

reduction in travel time. Existing studies also showed that adverse weather increased traffic crash risks. A Canadian study revealed that urban crashes increased by 70 percent during precipitation.

3) The interviews of TOC users found that the frequency of providing weather forecasts (twice per day, and more when weather situations coming in) met the needs of divisions. The station of meteorologists in the control room made it convenient for communications and update of weather information.

4) The weather elements and the time scales of weather forecasts that divisions were most interested in varied, as described in the following table. Long-term forecasts (>5 days) were less important to TOC users, as compared to other forecasts.

Table 15: Important Weather Elements and Priority of Forecasts

Division	Most Useful Weather Information	Priority of Different Time Scales of Weather Forecasts
Incident Management	Severe storms; Road hazard information	1st priority: Short-term (6~24 hrs)
Traffic Management	Road temperature; High winds on corridors; Weather inversions	1st priority: Medium-term (1~5 days) 2nd priority: Short-term
ATMS	All information	Varied
Signal Systems	Severe storms	1st priority: Nowcasts (1~6 hrs) 2nd priority: Short-term
Public Safety	Snow storms	Priority decreases from nowcasts to long-term forecasts

5) The interviews with TOC users showed that the interviewees were very satisfied with the weather service provided by the Program. The divisions relied heavily on the Program for weather information. Most of the divisions did not use other weather information sources. All of the responses indicated that TOC users will continue or increase using weather forecasts.

6) The interviews revealed that the use of the Program's weather forecasts was beneficial for TOC users. The benefits to each of the five divisions are illustrated in the following figure. In general, the Program helps divisions organize their staffs in a more effective way so they can be better prepared for forthcoming weather situations.

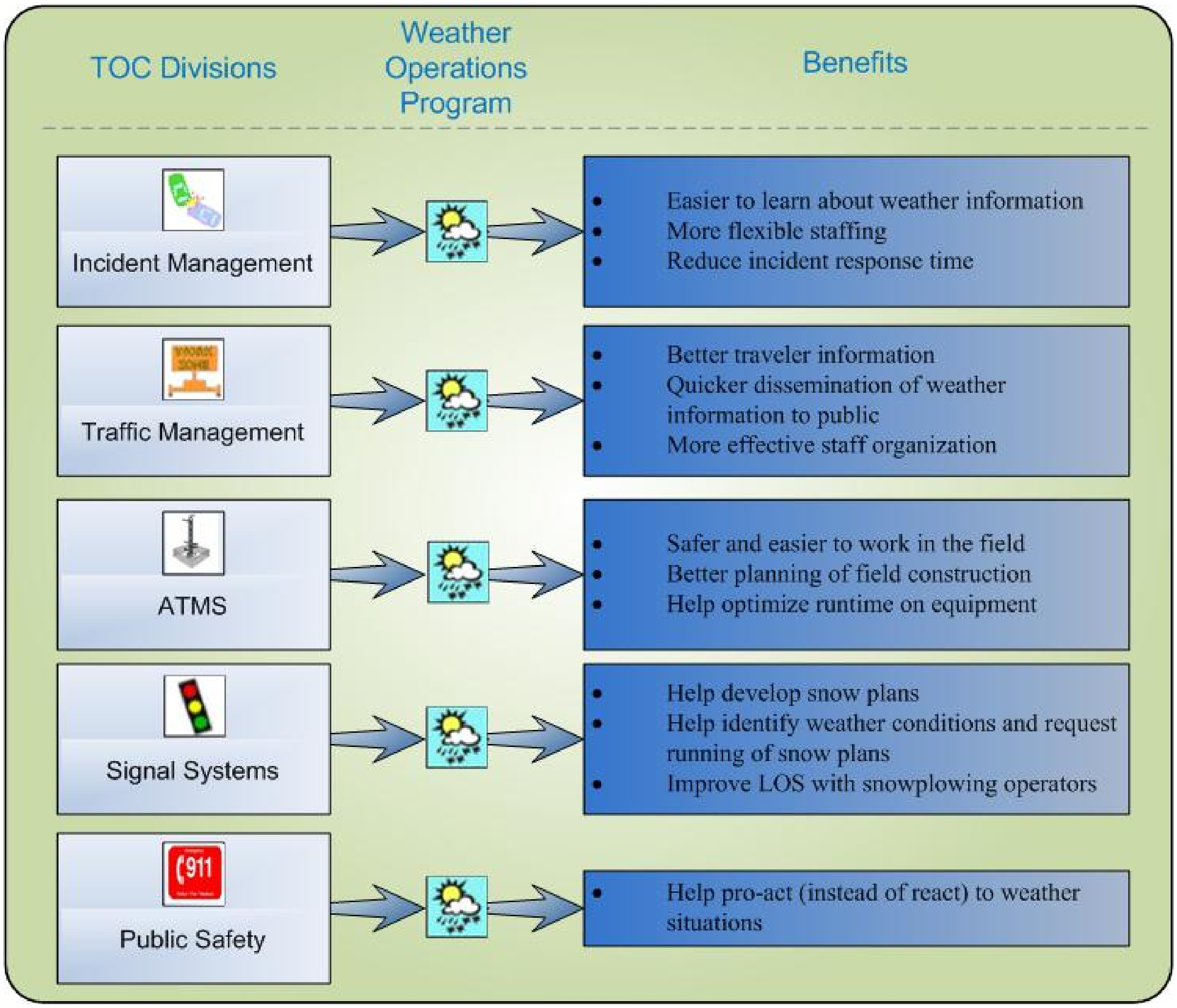


Figure 5: Benefits of the Program to TOC Users

APPENDIX A: EXAMPLE OF WEATHER FORECASTS

NorthWest Weathernet Inc.

In Partnership with

24/7 Personal Contacts
Toll Free- 1-866-291-4514
(801) 887-3703

UDOT Traffic Operations Center, Weather Desk
Region 2
Forecaster:

Date: 02/26/09
Time: 02:16

Region 2 Discussion:

Expect dry weather to start the day across the region with rain/snow showers increasing again after 1200 toward Wendover and by 14/1500 in Salt Lake valley. General snow level will fall to around 5000 ft by 1800. Road snow levels fall to around 6500 ft by 1800. No road snow concerns are expected for the evening commute in the valley outside of wet roads. Scattered valley showers decrease by around 1900 with a couple flakes possibly mixing into the valley at the end of the showers. Expect shower activity to fill back in across Salt Lake and Tooele valleys after 2200 as snow showers with colder air moving into the region. This round of snow showers will give the best shot at any road snow in the valley with greatest threat on bridges/overpasses. Heaviest of the valley snow showers likely ends by around 02/0300, but will not be completely dry through 0600 as there will likely be some light snow showers building off the lake. Continued mountain snow showers are expected through the night.

Region 2 Extended Forecast:

Couple valley flurries will be around for the morning commute with additional light bridge accumulations possible before 0900, then roads turn wet. Mountain snow showers linger through midday then decrease with roads likely wet by 1000 there. Dry weather returns for Friday night through Sunday with next chance of rain/snow showers Sunday night, watch for updates.

2421 Wendover

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1200. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Mainly dry start to the evening, snow shower threat mainly toward Grassy between 2100 and 0300. 1" or so possible Grassy, likely wet elsewhere. Some ice concern overnight where roads are wet.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Wendover POE	Hi 49	SW	10-20	25	Mostly Cloudy
Thu Night	Wendover POE	Lo 29	W	0-10		Mostly Cloudy
Thu	Grassy RWIS	Hi 54	SW	10-20	24	Mostly Cloudy
Thu Night	Grassy RWIS	Lo 28	W	0-10		Mostly Cloudy

2422 Grantsville

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1300. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Mainly dry start to the evening, snow shower threat increases after 21/2200, heaviest before 02/0300, but not dry through 0600. 1/2-1" shed/I-80, less south end of 196. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Grantsville Shed	Hi 51	SW	0-10		Mostly Cloudy
Thu Night	Grantsville Shed	Lo 27	NW	0-10		Cloudy
Thu	Grassy Shed	Hi 51	SW	10-20	24	Mostly Cloudy
Thu Night	Grassy Shed	Lo 28	NW	0-10		Cloudy
Thu	Lakepoint RWIS	Hi 48	SW	0-10		Mostly Cloudy
Thu Night	Lakepoint RWIS	Lo 28	NW	0-10		Cloudy

2423 Tooele

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 13/1400, mixing with snow late Johnson's. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Mainly dry 1800 through 2200 then snow shower threat increases after 2200. Heaviest snow before 02/0300, but not dry through 0600. 1/2-1" slop Stansbury, 1" maybe 2" Tooele, 2-3" Johnsons. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Tooele Shed	Hi 53	SW	0-10		Mostly Cloudy
Thu Night	Tooele Shed	Lo 27	NW	0-10		Mostly Cloudy
Thu	Johnson's Pass	Hi 45	SW	10-20	22	Mostly Cloudy
Thu Night	Johnson's Pass	Lo 28	NW	0-10		Mostly Cloudy
Thu	Five Mile Pass	Hi 48	S	0-10		Mostly Cloudy
Thu Night	Five Mile Pass	Lo 26	NW	0-10		Mostly Cloudy

2424 Salt Lake, West

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 14/1500. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Mainly dry 1800 through 2200 then snow shower threat increases after 2200. Heaviest snow before 02/0300, but not dry through 0600. 1/2-1" slop I-80, 1" maybe 2" Bacchus. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Redwood RWIS	Hi 50	S	0-10		Mostly Cloudy
Thu Night	Redwood RWIS	Lo 27	NW	0-10		Cloudy
Thu	Kennecott Smelter	Hi 48	SW	0-10		Mostly Cloudy
Thu Night	Kennecott Smelter	Lo 27	NW	0-10		Cloudy

2425 Salt Lake, East

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1500. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Few sprinkles evening hours mainly bench, snow threat increases after 2200. Heaviest snow before 0300, but not dry through 0600. 1/2-1" slop lower valley, 1" maybe 2" Capitol/University. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Spaghetti Bowl	Hi 51	S	0-10		Mostly Cloudy
Thu Night	Spaghetti Bowl	Lo 27	NW	0-10		Cloudy
Thu	University of Utah	Hi 51	S	0-10		Mostly Cloudy
Thu Night	University of Utah	Lo 28	NW	0-10		Cloudy

2427 Bluffdale

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 15/1600. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Few sprinkles evening hours mainly Point, snow threat increases after 2200. Heaviest snow before 0300, but not dry through 0600. 1/2-1" slop lower valley, 1" maybe 2" Point. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	I-15 9000S RWIS	Hi 52	S	0-10		Mostly Cloudy
Thu Night	I-15 9000S RWIS	Lo 27	NW	0-10		Mostly Cloudy
Thu	Point of the Mtn RWIS	Hi 48	S	0-10		Mostly Cloudy
Thu Night	Point of the Mtn RWIS	Lo 27	NW	0-10		Mostly Cloudy

2430 Salt Lake, North

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1500. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Mainly dry 1800 through 2200 then snow shower threat increases after 2200. Heaviest snow before 02/0300, but not dry through 0600. 1/2-1" slop throughout. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	SLC Airport	Hi 50	S	0-10		Mostly Cloudy
Thu Night	SLC Airport	Lo 27	NW	0-10		Cloudy

2431 West Jordan

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1500, mixing with snow Copperton. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Mainly dry 1800 through 2200 then snow shower threat increases after 2200. Heaviest snow before 02/0300, but not dry through 0600. 1/2-1" slop valley, 1" maybe 2" Bacchus, 1-3" Copperton. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	West Jordan Shed	Hi 51	S	0-10		Mostly Cloudy
Thu Night	West Jordan Shed	Lo 29	NW	0-10		Mostly Cloudy
Thu	Bacchus RWIS	Hi 49	S	0-10		Mostly Cloudy
Thu Night	Bacchus RWIS	Lo 29	NW	0-10		Mostly Cloudy
Thu	Copperton	Hi 49	S	0-10		Mostly Cloudy
Thu Night	Copperton	Lo 30	NW	0-10		Cloudy

2432 Murray

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1500. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Mainly dry 1800 through 2200 then snow shower threat increases after 2200. Heaviest snow before 02/0300, but not dry through 0600. 1/2-1" slop throughout. Most road snow focused on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	I-215/I-15 Interchange	Hi 52	S	0-10		Mostly Cloudy
Thu Night	I-215/I-15 Interchange	Lo 27	NW	0-10		Mostly Cloudy

2433 Cottonwood/East Benches

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1500, snow showers developing mainly after 1400 canyons. Wet roads are expected below 6500 ft with Tr-2" road snow upper canyons.

Road forecast Thu Night 18:00 - 6:00

Snow shower threat continues through the night at times canyons, main valley snow threat after 2200. 1/2-1" slop lower valley most on bridges, 1" maybe 2" Bench, 2-4"+ canyons. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Knudsen RWIS	Hi 51	S	0-10		Mostly Cloudy
Thu Night	Knudsen RWIS	Lo 28	NW	0-10		Cloudy
Thu	I-215 Bench (Olympus Cove)	Hi 47	S	0-10		Cloudy
Thu Night	I-215 Bench (Olympus Cove)	Lo 26	NW	0-10		Cloudy
Thu	Alta Shed	Hi 29	SW	0-10		Cloudy
Thu Night	Alta Shed	Lo 14	NW	0-10	21	Cloudy
Thu	Brighton Shed	Hi 34	S	0-10		Cloudy
Thu Night	Brighton Shed	Lo 18	NW	0-10		Cloudy

2434 Parleys Canyon Area

Road forecast Thu 06:00 - 18:00

Rain showers developing mainly after 1500, mixing with snow down to 5000 ft late. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Snow shower threat continues at times through the night in the canyon, main valley snow threat after 2200. 1/2-1" slop lower valley, 1" maybe 2" Bench, 1-3" Lambs. Greatest accumulation threat on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Sugarhouse	Hi 52	S	0-10		Mostly Cloudy
Thu Night	Sugarhouse	Lo 27	NW	0-10		Cloudy
Thu	Mouth of Parleys RWIS	Hi 47	S	0-10		Cloudy
Thu Night	Mouth of Parleys RWIS	Lo 26	NW	0-10		Cloudy
Thu	Parleys Canyon RWIS	Hi 44	S	0-10		Cloudy
Thu Night	Parleys Canyon RWIS	Lo 22	NW	0-10		Cloudy
Thu	Lambs Canyon	Hi 43	S	0-10		Cloudy
Thu Night	Lambs Canyon	Lo 22	NW	0-10		Cloudy

2435 Lamar Richins/Silver Creek

Road forecast Thu 06:00 - 18:00

Snow showers developing mainly after 1500. Wet roads are expected below 6500 ft with Trace road snow in town late, Tr-1/2" Parley's summit late.

Road forecast Thu Night 18:00 - 6:00

Snow shower threat continues at times through the night, heaviest before 03/0400, but not dry through 0600. 1-3" Parley's/Mayflower, 1" or so in town. Greatest accumulation threat on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Silver Creek RWIS	Hi 43	S	0-10		Cloudy
Thu Night	Silver Creek RWIS	Lo 14	NW	0-10		Cloudy
Thu	Mayflower Summit RWIS	Hi 40	S	0-10		Cloudy
Thu Night	Mayflower Summit RWIS	Lo 20	NW	0-10		Cloudy
Thu	Parleys Summit RWIS	Hi 41	S	0-10		Cloudy
Thu Night	Parleys Summit RWIS	Lo 21	NW	0-10		Cloudy

2436 Wanship

Road forecast Thu 06:00 - 18:00

Rain/snow changing developing mainly after 1500 and changing to all snow. Wet roads are expected.

Road forecast Thu Night 18:00 - 6:00

Hit/miss snow shower threat continues through around 0300 then just a stray flurry. 1" or so accumulation. Greatest accumulation threat on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Silver Creek Canyon	Hi 41	S	0-10		Cloudy
Thu Night	Silver Creek Canyon	Lo 17	NW	0-10		Cloudy
Thu	Coalville	Hi 44	S	0-10		Mostly Cloudy
Thu Night	Coalville	Lo 21	NW	10-20		Mostly Cloudy

2437 Kamas

Road forecast Thu 06:00 - 18:00

Snow showers developing mainly after 15/1600. Wet roads are expected below 7000 ft with Tr-1/2" road snow canyons.

Road forecast Thu Night 18:00 - 6:00

Snow shower threat continues through the night, heaviest before 0300, but not dry through 0600. 1" in town, 1-3" canyons. Greatest accumulation threat on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Kamas Shed	Hi 41	S	0-10		Mostly Cloudy
Thu Night	Kamas Shed	Lo 21	NW	0-10		Mostly Cloudy
Thu	Soapstone	Hi 36	S	0-10		Mostly Cloudy

Thu Night	Soapstone	Lo 21	NW	0-10		Cloudy
Thu	SR248 RWIS	Hi 42	S	0-10		Mostly Cloudy
Thu Night	SR248 RWIS	Lo 19	NW	0-10		Mostly Cloudy
Thu	Wolf Creek Summit	Hi 33	SW	0-10		Mostly Cloudy
Thu Night	Wolf Creek Summit	Lo 21	NW	10-20	23	Cloudy

2438 Echo

Road forecast Thu 06:00 - 18:00

Rain/snow changing developing mainly after 1500 and changing to all snow. Wet roads are expected at this time.

Road forecast Thu Night 18:00 - 6:00

Hit/miss snow shower threat continues through around 0300 then just a stray flurry. 1" or so accumulation. Greatest accumulation threat on bridges/overpasses. Ice concerns.

Time Period	Where	Temp	Dir	Wind	Gust	Sky
Thu	Wahsatch Hill	Hi 39	SW	10-20	24	Mostly Cloudy
Thu Night	Wahsatch Hill	Lo 18	NW	15-25	24	Cloudy
Thu	Hennefer	Hi 39	S	0-10		Cloudy
Thu Night	Hennefer	Lo 18	NW	10-20	21	Cloudy

APPENDIX B: INTERVIEW QUESTIONS

- **ATMS Division**

1. What are the daily activities in your division? What are the normal hours of operation?
2. What would your division do without the existence of the Weather Operations Program?
3. What are your responsibilities in the division? Does your division call the weather operations offices for weather information? If so, when will your division call?
4. How often does your division receive weather forecasts from the weather operations office?
5. How often does your division use weather forecasts from the weather operations office? Or under what situations will weather forecasts be used?
6. Does your division use weather information from other resources? If so, what are the weather sources? And what are the frequencies of using them?
7. What is the general process of applying weather forecasts to ATMS?
8. How has the Weather Operations Program changed the way you do your job?
9. What are the traffic management systems that weather forecasts are applied to?
10. What are the weather forecast elements that your division is most interested in?
11. What are the priority rankings for different time scales of weather forecasts used by your division? The time scales include: nowcast (1–6 hrs), short-term forecast (6 hrs–24 hrs), medium-term forecast (1 day–5 days), and long-term forecast (> 5 days).
12. What are the benefits that your division has achieved by using weather forecasts from the weather operations office?
13. Do you have specific examples about how the lack of timely/precise/appropriate weather information hampered your efforts?
14. What is the tendency (in terms of frequency) of using weather forecasts in the future?

- **Traffic Management Division**

1. What are the daily activities in your division? What are the normal hours of operation?
2. What would your division do without the existence of the Weather Operations Program?

3. What are your responsibilities in the division? Does your division call the weather operations offices for weather information? If so, when will your division call?

4. How often does your division receive weather forecasts from the weather operations office?

5. How often does your division use weather forecasts from the weather operations office? Or under what situations will weather forecasts be used?

6. Does your division use weather information from other resources? If so, what are the weather sources? And what are the frequencies of using them?

7. What is the general process of applying weather forecasts to operations?

8. How has the Weather Operations Program changed the way you do your job?

9. What are the weather forecast elements that your division is most interested in?

10. What are the priority rankings for different time scales of weather forecasts used by your division? The time scales include: nowcast (1-6 hrs), short-term forecast (6 hrs–24 hrs), medium-term forecast (1 day–5 days), and long-term forecast (>5 days).

11. What are the benefits that your division has achieved by using weather forecasts from the weather operations office?

12. Do you have specific examples about how the lack of timely/precise/appropriate weather information hampered your efforts?

13. What is the tendency (in terms of frequency) of using weather forecasts in the future?

- **Incident Management Team (IMT)**

1. What are the daily activities in your division? What are the normal hours of operation?

2. What would your division do without the existence of the Weather Operations Program?

3. Does your division call the weather operations offices for weather information? If so, when will your division call?

4. How often does your division receive weather forecasts from the weather operations office?

5. How often does your division use weather forecasts from the weather operations office? Or under what situations will weather forecasts be used?

6. Does your division use weather information from other resources? If so, what are the weather sources? And what are the frequencies of using them?

7. What is the general process of applying weather forecasts to incident management?

8. How has the Weather Operations Program changed the way you do your job?
9. What are the weather forecast elements that your division is most interested in?
10. What are the priority rankings for different time scales of weather forecasts used by your division? The time scales include: nowcast (1-6 hrs), short-term forecast (6 hrs–24 hrs), medium-term forecast (1 day–5 days), and long-term forecast (>5 days).
11. (Please provide your answer as detail as possible.) What are the benefits that your division can achieve by using weather forecasts from the weather operations office?

    Specifically, has the incident response time been improved during weather events with the use of weather forecasts?
12. Are there any data (e.g., crash data, incident response time) or information to show the improvement of incident management by using weather forecasts?
13. Do you have specific examples about how the lack of timely/precise/appropriate weather information hampered your efforts?
14. What is the tendency (in terms of frequency) of using weather forecasts in the future?

- **Signal Systems Division**

1. What are the daily activities in your division? What are the normal hours of operation?
2. What would your division do without the existence of the Weather Operations Program?
3. What are your responsibilities in the division? Does your division call the weather operations offices for weather information? If so, when will your division call?
4. How often does your division receive weather forecasts from the weather operations office?
5. How often does your division use weather forecasts from the weather operations office? Or under what situations will weather forecasts be used?
6. Does your division use weather information from other resources? If so, what are the weather sources? And what are the frequencies of using them?
7. What is the general process of applying weather forecasts to signal timing?
8. How has the Weather Operations Program changed the way you do your job?
9. What are the weather forecast elements that your division is most interested in?

10. What are the priority rankings for different time scales of weather forecasts used by your division? The time scales include: nowcast (1-6 hrs), short-term forecast (6 hrs–24 hrs), medium-term forecast (1 day–5 days), and long-term forecast (>5 days).

11. Is current weather information used to adjust signal timing?

12. Are weather forecasts used to proactively change signal timing?

13. Is signal timing based on pre-set plans for different conditions (e.g. a light snow timing plan, a rain timing plan)?

14. What are the benefits that your division has achieved by using weather forecasts from the weather operations office?

14. Are there any data or information to show the effectiveness of weather-responsive signal timing plans?

15. Do you have specific examples about how the lack of timely/precise/appropriate weather information hampered your efforts?

16. What is the tendency (in terms of frequency) of using weather forecasts in the future?

- **Department of Public Safety**

1. What are the daily activities in your division? What are the normal hours of operation?

2. What would your division do without the existence of the Weather Operations Program?

3. What are your responsibilities in the division? Does your division call the weather operations offices for weather information? If so, when will your division call?

4. How often does your division receive weather forecasts from the weather operations office?

5. How often does your division use weather forecasts from the weather operations office? Or under what situations will weather forecasts be used?

6. Does your division use weather information from other resources? If so, what are the weather sources? And what are the frequencies of using them?

7. What is the general process of applying weather forecasts to highway patrol?

8. How has the Weather Operations Program changed the way you do your job?

9. What are the weather forecast elements that your division is most interested in?

10. What are the priority rankings for different time scales of weather forecasts used by your division? The time scales include: nowcast (1-6 hrs), short-term forecast (6 hrs–24 hrs), medium-term forecast (1 day–5 days), and long-term forecast (>5 days).

15. What are the benefits that your division has achieved by using weather forecasts from the weather operations office?

11. Do you have specific examples about how the lack of timely/precise/appropriate weather information hampered your efforts?

12. What is the tendency (in terms of frequency) of using weather forecasts in the future?

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