

## **Research Needs for Weather-Responsive Traffic Management**

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**Abstract.** Weather-responsive traffic management views weather events as non-recurring incidents that can be predicted, observed, and mitigated. This paper reports weather impacts on traffic flow and describes an emerging concept of operations for a system-wide approach to traffic management in adverse weather. The paper discusses this structured approach to assess weather impacts and implement operational strategies that improve safety, mobility, and productivity. Finally, research needs to advance the state-of-the-practice in weather-responsive traffic management are enumerated.

## **INTRODUCTION**

Traffic managers implement a number of strategies such as operating traffic signals on arterial routes, controlling traffic flow on freeways, detecting and managing incidents, and disseminating traveler information to ensure roadway safety and minimize congestion. Weather events and their impacts can be viewed as predictable, non-recurring incidents that contribute to congestion by reducing capacity—the maximum flow rate at which vehicles can traverse a roadway over a given time period. Every day, weather affects traffic on every road in the nation by impacting pavement conditions, vehicle performance, and driver behavior. Consequently, there is a need for a systematic approach to the significant challenge of managing traffic during inclement weather.

With this in mind, weather-responsive traffic management strategies can be planned and implemented to mitigate weather effects on traffic flow. As with any incident, managers must be able to predict or detect a weather event, assess the nature of the event (e.g., severity, impact area), and manage traffic under less-than-optimal conditions. To prevent weather-related congestion, and lessen the impact of unavoidable congestion, traffic managers need to understand how weather impacts roads and traffic, as well as the benefits of weather-responsive strategies. In spite of the ability to prepare for and manage such incidents, the field of weather-responsive traffic management is in its infancy. This subject is addressed in this paper, which discusses a weather-responsive traffic management concept of operations, developed under the Federal Highway Administration (FHWA) Road Weather Management Program, and research needs to advance the state-of-the-practice in this field.

## **WEATHER IMPACTS ON ROADS AND TRAFFIC**

Weather events such as precipitation, fog, high winds, high water, and extreme temperatures reduce roadway capacity. These events can cause slick pavement, lower traffic speeds, increase speed variability (i.e., a measure of speed uniformity), affect traffic volume, increase delay, and escalate crash risk. Weather impacts can also disrupt access to roads (i.e., lane obstruction or submersion, pavement buckling), and damage road infrastructure (e.g., traffic control devices, communications systems). Large segments of many metropolitan road networks are currently operating at or near capacity. As congestion increases in urban areas, weather events will have an even greater impact on traffic flow (1).

All forms of precipitation can impact traffic operations. Light rainfall or snowfall after extended periods with no precipitation can cause slippery pavement when water mixes with oil, and can reduce freeway speeds by roughly 10 percent. In addition to reducing vehicle traction, heavy rain or snow can reduce visibility distance and cause drivers to increase headway (i.e., or spacing between vehicles), decrease acceleration rates, and reduce freeway speeds by 16 to 40 percent (2, 3). Arterial speeds decline by 10 to 25 percent in rainy, wet pavement conditions and by 30 to 40 percent with snowfall and snowy/slushy pavement (3).

In poor road weather conditions, arterial traffic volumes can decline by six to 30 percent, depending on the time of day (3). A study of Iowa freeways found that traffic volumes decrease by 22 to 36 percent during snowstorms. This study also found that volumes can increase during the early hours of a snowstorm, especially on weekdays (4). A study of weather impacts on a Texas freeway found that rain reduced capacity by 14 to 19 percent (5). It was estimated that, in 1999, capacity on U.S. freeways and principle arterials was reduced by more than 11 percent due to fog, snow and ice (6).

Weather can reduce the effectiveness of traffic signal timing plans designed for use in clear, dry pavement conditions. On arterials with coordinated traffic signals, start-up delay is five percent higher on wet pavement, 23 percent higher in snowy pavement conditions, and 50 percent higher during snowstorms. The number of vehicle stops in adverse weather increases by 14 percent. Travel time delay on signalized routes can increase by 11 to 50 percent depending on weather event severity (3). Analyses of travel time delay on freeways in metropolitan

Washington, DC demonstrated that average off-peak, travel time increased by 14 percent in the presence of precipitation, high winds, low visibility, and/or slick pavement. A more detailed analysis using Doppler radar data indicated that, during peak periods, travel time increases by roughly 24 percent with precipitation (1). A separate study estimated that, in 1999, 23 percent of the non-recurrent delay on freeways and major arterials was due to snow, ice, and fog events (6).

While snow and ice may be perceived as the greatest threats to traffic operations, national crash statistics indicate that rain and wet pavement have more significant impacts on road safety (7). In 2001, nearly 79 percent of weather-related crashes in passenger vehicles occurred on wet pavement and nearly 49 percent happened during rainfall. Further, most hurricane-related deaths result from inland flooding on roads, due to rain after landfall. Over 22 percent of passenger vehicle crashes in 2001 happened under adverse road weather conditions. Each year over 450,000 injury crashes and nearly 6,500 fatal crashes in passenger vehicles take place in rain, sleet, snow, or fog; or when pavement conditions are wet, snowy/slushy, or icy. In 2001, over 615,000 people were injured and more than 6,900 people were killed in these weather-related crashes. In that same year, nearly 19 percent of large truck crashes (i.e., nearly 77,800) occurred on wet, snow-covered, slushy, or icy pavement. Nearly 12 percent of these crashes (i.e., over 48,500) happened in rain, snow, sleet, or fog.

When fog, drifting snow, or blowing dust reduce visibility some drivers reduce speed more than others, increasing speed variance and the risk of overtaking crashes. An analysis of a fog-prone freeway in Utah found that “overly cautious” or “confused” drivers travel at speeds 20 to 50 percent lower than other drivers (9). Multi-vehicle, chain-reaction crashes occurring in low-visibility conditions result in fatalities, multiple injuries, and extended road closures. High winds can blow snow, dust, or debris (e.g., tree branches) across roadways causing visibility restrictions and lane obstructions. High winds can also impact vehicle stability by causing vehicles—particularly high-profile tractor-trailers—to be blown over or blown off of roads. Such crashes can cause significant delay due to lane or road closures.

## **WEATHER-RESPONSIVE TRAFFIC MANAGEMENT CONCEPT OF OPERATIONS**

Tackling the impacts of weather on highway operations requires a structured, systematic approach. This evolving discipline is referred to in this paper as weather-responsive traffic management. New weather-responsive traffic management strategies will depend on better forecasts of weather, pavement, and traffic conditions. In this case “better” means timely, accurate, route-specific data at high resolutions comparable in scale to road network databases. As more Intelligent Transportation Systems (ITS) are deployed, Advanced Traffic Management Systems (ATMS) are becoming vital tools for managers and operators in Traffic Management Centers (TMCs). Integration of data from environmental monitoring systems with ATMS would provide managers with tailored decision support based on the unique configuration, characteristics, and microclimatology of an urban road network. The expectation is that, once equipped with this information, traffic managers will be able to take targeted actions to respond to or mitigate weather impacts on traffic flow.

To facilitate the development of such integrated solutions, a concept of operations for weather-responsive traffic management was drafted (10). This draft report is intended to initiate discussion about the development, testing, and deployment of effective traffic management tools for response to weather threats. It addresses weather information needs of traffic managers, road weather data collection, assessment of weather impacts, and the effects of various strategies on operational objectives. Building upon a number of successful tools that have been implemented to date, the concept of operations presents a systematic context consistent with broader traffic management strategies.

This framework will enable traffic managers to fully understand weather impacts and embrace tools to achieve more effective, efficient operations under weather threats. The concept of operations does not propose weather-responsive traffic management to be a new set of rules added to current practices. Rather, it proposes to better incorporate weather information and decision support into current operational procedures. With relevant road weather data integrated into the information stream, traffic managers will be able to better address the impacts of weather on operational objectives and expand the benefits of their systems.

## Assessment of Weather Impacts on Basic Operational Objectives

Under all conditions, independent of weather, traffic managers have three basic operational objectives that drive their decisions: ensuring road safety by reducing crash risk, improving mobility by achieving stable traffic flow, and increasing agency productivity by minimizing operating costs. Many managers operate from TMCs where ITS components allow them to centrally monitor road conditions and control traffic flow, disseminate pre-trip and en-route traveler information, as well as share data and coordinate with other managers. Based upon prevailing road weather conditions, managers can make decisions and take actions that optimize traffic flow on road networks.

Knowledge of prevailing conditions is gained by access to road weather information—both observations and predictions. The information from environmental observing systems can be used to track the location and movement of weather fronts and storm cells. Such dynamic weather assessments could result in targeted decision making by traffic managers, leading to more efficient network operation over the life of a weather event as it traverses a metropolitan area. When one considers that even minor changes in a single weather variable, such as air temperature, can cause one storm to produce snow during the morning peak period and rain in the evening, then it is clear that managers must have at their disposal many different strategies to achieve their objectives.

The concept of operations proposes that managers utilize road weather information, combined with traffic flow data, to assess the impact of various weather events on highways. Such information can then aid in the design and implementation of weather-responsive strategies that improve mobility and safety on road segments with increased congestion or more frequent crashes during adverse weather (e.g., fog-prone bridges, sharp curves). Transportation agencies can also enhance productivity when traffic managers coordinate and share resources with maintenance and emergency managers. The benefits of infrastructure investments can be maximized by integrating ATMS with Road Weather Information Systems (RWIS) deployed for winter maintenance or flood monitoring. A coordinated approach to system design and expansion (e.g., collocating weather sensors and vehicle detectors) can significantly reduce the costs of procuring, operating, and maintaining the infrastructure and information systems that support the basic operational objectives. Intra-agency coordination facilitates efficient traffic flow across jurisdictional boundaries, promotes more efficient personnel management (e.g., scheduling of TMC staff, snowplow drivers, and emergency responders), and reduces the time to treat routes or repair damaged infrastructure.

## Operational Strategies and Transportation Outcomes

To aid in this structured approach to weather-responsive traffic management, the concept of operations highlights three types of road weather management strategies—advisory, control, and treatment strategies (11). Advisory strategies provide information on prevailing and predicted conditions to the traveling public. In a manner similar to current travel advisories, traffic managers would utilize motorist warning systems to inform drivers of low visibility, slick pavement, high winds, and flooding. Strategies include activation of flashing beacons atop static signs, posting warnings on Dynamic Message Signs (DMS), and broadcasting messages via Highway Advisory Radio (HAR). The provision of road weather information is an advisory strategy used to influence the decisions of travelers (e.g., route choice, departure time, travel speed). Such advisory strategies are being deployed today in many areas. By integrating better atmospheric and pavement data with traffic flow, incident, and construction data, more timely and accurate messages could be communicated to travelers. Additionally, the information can serve as the basis of route-specific road condition reports and travel forecasts through web sites and interactive telephone systems (e.g., 511—the national traveler information telephone number).

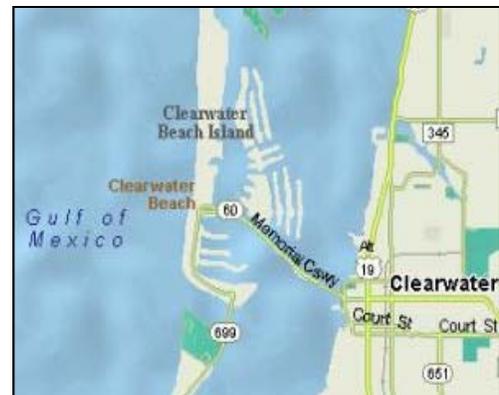
Advisory strategies are often used in combination with control strategies, which are another aspect of the concept of operations. Control strategies alter the state of roadway devices to permit or restrict traffic flow and regulate roadway capacity. Weather-related signal timing plans modify cycle lengths, splits, and offsets to accommodate changes in driver behavior and decrease arterial delay (e.g., vehicle stops). Speed management involves the determination of safe freeway speeds based upon visibility, pavement, traffic volume, and/or vehicle classification data. With an ITS, safe speeds can be computed and automatically conveyed to motorists via HAR, DMS, or Variable Speed Limit (VSL) signs. When travel conditions are unsafe, traffic managers may restrict access to affected bridges, specific lanes, entire road segments, or designated vehicle types (e.g., high-profile vehicles). Ramp gates, lane use control signs, flashing beacons, HAR, and DMS are typically employed to alert motorists of weather-related hazards and access restrictions.

Treatment strategies (e.g., anti-icing, fog dispersal) are the third type of strategy described in the concept of operation. These strategies supply resources, such as salt and sand, to roadways to minimize or eliminate weather impacts. Many treatment strategies involve coordination of traffic, maintenance, and emergency managers. By communicating and coordinating activities, these managers can quickly restore capacity lost to snow and ice accumulation, submerged lanes, or damaged infrastructure.

In the weather-responsive traffic management concept of operations, advisory, control, and treatment strategies are implemented in response to weather threats to help travelers make informed decisions and avoid hazards, reduce crash frequency and severity, decrease weather-related delay and congestion, as well as minimize operating and maintenance costs. Currently, these strategies are executed to mitigate localized weather impacts on relatively short road segments. To achieve weather-responsive traffic management benefits, as envisioned in the concept of operations, network-wide solutions are required to complement the site-specific strategies.

**Weather-Responsive Traffic Management Case Studies**

Case studies of successful operational strategies used on an arterial route, a freeway segment and a bridge are presented to illustrate how weather-responsive traffic management can improve transportation outcomes. In the City of Clearwater, Florida traffic signal timing is changed automatically during frequent afternoon thunderstorms. These storms cause significant increases in traffic exiting Clearwater Beach via the Memorial Causeway (i.e., State Route 60) shown in Figure 1. When an electric rain gauge near the beach senses a predetermined amount of rainfall, the signal system computer issues a preemption command to 14 signals along the route. Signal controllers execute new timing plans with longer green times for inbound approaches. When vehicle detector data indicates that the traffic volume has returned to normal, the central computer restores normal signal timing plans. By modifying traffic signal timing in response to rain, the signal system computer prevents traffic congestion and enhances mobility.



**FIGURE 1 City of Clearwater Map.**

The Idaho Department of Transportation (DOT) installed a motorist warning system on a 161-kilometer (100-mile) section of Interstate 84 that was prone to multi-vehicle crashes when visibility was reduced by blowing snow, blowing dust and/or precipitation. Data from environmental sensors and vehicle detectors deployed along the freeway are transmitted to a central computer. The computer sounds an alarm when field data indicates that visibility has fallen below a predetermined threshold or that driving conditions are deteriorating. When alerted, traffic managers decide which advisories to issue and activate DMS. As shown in Table 2, disseminating advisory information in hazardous conditions prompts drivers to reduce speed, which lowers crash risk and improves safety.

**TABLE 2 – Idaho DOT Safety Impacts**

Road Weather Conditions	Speed without Advisories	Speed with Advisories	Speed Reduction due to Advisories
High Winds (over 32.2 kph or 20 mph)	88.1 kph (54.8 mph)	68.0 kph (42.3 mph)	23 percent
High Winds & Precipitation	75.6 kph (47.0 mph)	66.2 kph (41.2 mph)	12 percent
High Winds & Snow-Covered Pavement	87.9 kph (54.7 mph)	56.9 kph (35.4 mph)	35 percent

Following a 193-vehicle crash on the Interstate 10 Bay Bridge in 1995, the Alabama DOT deployed and began operating a fog warning system in September 2000. Video from Closed Circuit Television (CCTV) cameras and data from visibility sensors installed on the seven-mile bridge are transmitted to a central computer. When fog is observed via CCTV, operators consult the computer to view visibility distance in six independently operated zones. As shown in Table 1, warnings are posted on DMS and speed limits are reduced with VSL signs based upon conditions in each zone. In very low visibility, Highway Patrol officers are dispatched to close the bridge. The warning system has improved safety by reducing average speed and minimizing crash risk in low visibility conditions.

**TABLE 1 – Alabama DOT Low Visibility Warning System Strategies**

Visibility Distance	Advisories on DMS	Other Strategies
Less than 274.3 m (900 ft.)	“FOG WARNING”	Speed limit at 65 mph (104.5 kph)
Less than 201.2 m (660 ft.)	“FOG” alternating with “SLOW, USE LOW BEAMS”	<ul style="list-style-type: none"> <li>• “55 MPH” on VSL signs</li> <li>• “TRUCKS KEEP RIGHT” on DMS</li> </ul>
Less than 137.2 m (450 ft.)	“FOG” alternating with “SLOW, USE LOW BEAMS”	<ul style="list-style-type: none"> <li>• “45 MPH” on VSL signs</li> <li>• “TRUCKS KEEP RIGHT” on DMS</li> </ul>
Less than 85.3 m (280 ft.)	“DENSE FOG” alternating with “SLOW, USE LOW BEAMS”	<ul style="list-style-type: none"> <li>• “35 MPH” on VSL signs</li> <li>• “TRUCKS KEEP RIGHT” on DMS</li> <li>• Street lighting extinguished</li> </ul>
Less than 53.3 m (175 ft.)	I-10 CLOSED, KEEP RIGHT, EXIT ½ MILE	Road Closure by Highway Patrol

**RESEARCH NEEDS TO SUPPORT THE CONCEPT OF OPERATIONS**

Additional work is needed to advance the state-of-the-practice and make the concept of operations a reality. Better analysis tools, models, and integrated solutions will lead to more efficient operation of highways during adverse weather. The concept of operations highlighted the following key questions.

- What data, processes, and procedures are needed by traffic managers to support weather-responsive traffic management?
- How should weather-related data, processes, and procedures be integrated with other transportation management systems and activities?
- What additional resources are needed to support weather-responsive traffic management?

To provide traffic managers with decision support, further research must be conducted to design, prototype, and test high-resolution predictions of surface weather, pavement, and traffic conditions. Investigators must determine how different weather events impact traffic demand, travel speeds, and roadway capacity to examine and understand weather effects on intersection, interchange, and overall network operation. To that end, FHWA recently initiated a study to baseline the use of weather information in TMCs. This study builds upon a brief FHWA survey, conducted in 2001, which revealed that most TMCs receive some general weather information and over 60 percent use customized weather products (e.g., pavement temperature predictions). Only a few of the centers integrated weather data into operating systems.

Applied research conducted in TMCs will help system developers understand user needs, integrate pavement and weather data with ATMS, and determine the most effective means of presenting environmental information to traffic operators. Research is also required to provide additional resources and develop systematic weather-responsive traffic management strategies. Key issues to be explored include better understanding of driver behavior in adverse

conditions (e.g., headway, lane-changing, speed) and delivery of road weather information (e.g., message sets) to various types of travelers (e.g., commuters, tourists, commercial vehicle operators).

Given these extensive research needs, it seems reasonable to pursue a broader road weather research program. Resources to carry out road weather data collection and research are currently inadequate, undedicated, and limited by authorization levels. The FHWA Road Weather Management Program advocates the establishment of a national steering committee of transportation, public safety, and meteorological professionals to promote a research agenda including advanced weather research and applied research to prototype and validate integrated solutions for transportation managers.

## **CONCLUSION**

Weather-responsive traffic management is a truly interdisciplinary endeavor requiring a thorough understanding of the impact of adverse weather on safety, mobility, and operations. Armed with accurate, timely, route-specific road weather information, traffic managers can apply a variety of strategies in a systematic manner to achieve optimal traffic flow on freeways and arterials in urban road networks. Current practice has shown that weather-responsive traffic management strategies are effective when applied to short highway segments. To fully achieve 21<sup>st</sup> century operations with 21<sup>st</sup> century technologies, additional research and development are needed to advance integrated, network-wide solutions for advising travelers and controlling traffic flow in adverse weather.

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