APPROACHES AND GAPS IN WEATHER RESPONSIVE TRAFFIC MANAGEMENT –
US AND EUROPEAN PERSPECTIVES

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ABSTRACT

Traffic management and operations during adverse weather is a major challenge for transportation agencies around the world. Weather is a common cause of crashes and delays on the highways everywhere, accounting for large number of fatalities and hours of delay every year in the US and Europe. Significant improvements have been made in the development and implementation of weather responsive traffic management (WRTM) strategies to alleviate the impacts of weather, both in the US and Europe. These include weather and traffic data collection and integration, traffic analysis and modeling, human factors analysis and performance evaluation. The paper describes the state-of-the practice in weather-responsive traffic management in the US and Europe including the types of strategies, systems and tools being used, their similarities, and their effectiveness in traffic operations. Gaps in current practices and research related to weather-responsive traffic management are identified, and recommendations on how these gaps can be filled are described. The paper also describes the relevant research activities being undertaken in both regions and how they can coordinate and benefit from each other’s efforts.
1. BACKGROUND

1.1 Weather and Traffic in the US and Europe

Adverse weather affects the performance of the highway system everywhere, resulting in crashes, delays and significant economic losses. In the US, more than 1.5 million highway crashes per year can be attributed to bad weather, causing more than 7,000 fatalities and close to 700,000 injuries (1). It is also the second leading cause of non-recurring highway congestion, contributing about 25% of delays on the freeways. About 1 billion hours are lost each year on the U.S. highway system due to weather-related delays. Figure 1 shows the economic impacts in 15 US States of closing the roads for one day due to a storm.

![FIGURE 1 – Fiscal Impacts of One-Day Road Closure due to Storm in 15 US States (Source: (2))](image)

Similarly in France, 2007 accident statistics showed that 13% of injury accidents occur during light rain or strong rain (3). Lack of visibility during inclement weather conditions constitutes an important issue with over 100 annual fatalities attributed to low visibility.

1.2 Need to Understand and Model Impacts of Weather on Traffic Flow

Weather events like rain, snow, sleet, fog, and high winds can change the driving environment by decreasing visibility distance, causing slippery pavement, obstructing lanes, and damaging...
infrastructure, among others. These weather-related changes in the roadway environment affect traffic operations by decreasing vehicle speeds and traffic volumes, reducing roadway capacity and saturation flow rates, and increasing speed variance and start-up delays. Nothing can be done to change the weather, but its impacts on traffic operations can be alleviated if applicable models and analysis tools exist to support decision-making by transportation agencies.

There is a need for traffic managers and operators to understand the relationship between weather and traffic flow, and use this knowledge in developing and implementing appropriate intervention strategies. Currently, most transportation planners and traffic analysts use models that assume ideal conditions (i.e., clear weather and dry pavement). Incorporating weather effects into traffic models would increase their usefulness and ability to contribute to development of weather-responsive strategies. Advances in weather sensing and prediction as well as improved communications and analysis capabilities allow more accurate condition/impact forecasting and more proactive management of traffic in inclement weather conditions.

In the US and many European countries, significant knowledge now exists about the relationships between various weather events and traffic flow parameters. Research on traffic behavior under adverse weather conditions, including rain, snow, high winds and fog, have been conducted to determine, both at the macroscopic and microscopic levels, how traffic parameters such as speed, density, capacity, volume, headways and critical gaps, are affected by various types and intensities of the weather events.

1.3 Purpose of the Paper

This purpose of this paper is to describe the state-of-the-practice in weather responsive traffic management (WRTM) in the US and Europe including the types of strategies and analytical tools being used, their similarities, and their effectiveness in traffic operations. The paper also describes the relevant research activities being undertaken in both continents and how those efforts can be coordinated to achieve common objectives. Specifically, the paper summarizes relevant results and findings from major research programs undertaken by the FHWA Road Weather Management Program in the USA and TU0702 COST partnership in Europe dealing with real-time monitoring, surveillance and control of road networks under adverse weather conditions. Finally, the paper identifies the gaps in current practices and research related to weather-responsive traffic management, and provides recommendations on how those gaps can be filled.

2. EXISTING APPROACHES TO WEATHER RESPONSIVE TRAFFIC MANAGEMENT

2.1 Weather and Traffic Data Collection and Integration

Timely and accurate traffic and weather data are important because they enable transportation agencies to manage traffic conditions in real time in response to existing and impending weather conditions, and to inform or warn motorists about these conditions and how they will affect their trips. Without weather data coming into the transportation management centers (TMCs), the
ability to respond to weather is limited. Historically, road managers pulled weather and traffic
data from static and fixed devices such as video cameras, traffic counters, loop detectors, airport
weather stations, and environmental sensor stations. Advancements in mobile sensing and
communications, road weather information systems, weather and traffic data collection and
integration, and prediction/forecasting technologies including those that have spawned from
Intelligent Transportation Systems, provide opportunities to better understand how weather
conditions impact travel and conversely how drivers behave in adverse weather and how their
decisions affect traffic flow. Ultimately, these technologies can support WRTM strategies such
as real-time modification of traffic signal and ramp meter timing, operation of automated deicing
systems, and setting of variable speed limits (4).

In the US, significant federal and non-federal sources exist for the collection of a broad range of
weather data types. The National Weather Observation System (NWOS) operated by NOAA
(National Oceanic Atmospheric Administration) acquires a broad range of weather information
to support the weather information needs for operational and research efforts. Non-federal data
collection is conducted by the public and private sector including State DOT’s. Sources of
weather information range from space-based to surface-based platforms. Geostationary weather
satellite data provides a near continuous source of data for weather monitoring. The data is
collected from polar orbiting and geostationary weather satellite. Weather radar data is a major
source of data for short-term weather forecasting and decision making. Environmental Sensor
Stations (ESS) are the principal weather data collection systems used by state DOTs. The data
collected by ESS include both atmospheric and pavement data. The atmospheric data is often
similar to the data collected by other atmospheric observing systems such as at airports. The
pavement data is mostly unique in nature and highly site specific. ESS data collected over a
network is combined to define a road weather information system (RWIS).

In Europe, similar approaches exist to collect both weather and traffic data, even though there is
no federal approach at the European scale. Some national contexts can be included here. In
France, RWIS are designed by the three main toll motorway groups: Vinci, Eiffage and
Macquatie. Motorways are equipped with weather stations in addition to those owned by the
national meteorological agency (Meteo France). The RWIS on these motorways is provided by
the traffic operators (ASF, APRR, AREA, COFIROUTE, SENEF) and Météo-France, which
provide weather forecasts. In Austria, motorways are operated by the Austrian Road Operator
ASFINAG, the Austrian Railway Operator ÖBB and the Austrian Air Management Control
Agency Austrocontrol. Weather information is provided in addition to traffic information like
travel time and traffic-related events (e.g. road construction sites). Motorway users can access
information via Internet and mobile telephones with integrated internet browser. About 220
measurement stations are situated alongside the Austrian motorway network, which has a length
of about 2,500 miles of highway. In Denmark, 320 road weather stations are used primarily for
winter maintenance or wind warning on large bridges. The Danish Road Directorate administers
2,250 miles of roads, with an average of approximately one measuring station every 20 miles. In
the Czech Republic, the Czech Road Weather Information System feeds the National Traffic
Information Center. It integrates information from 450 road weather stations with the
meteorological forecast of the National Weather Service, camera pictures and regular thermal
mapping of the road network. In Northern Europe, weather conditions present major problems
during wintertime, but the region is equipped with advanced weather sensing technologies. The
Icelandic Road Administration (ICERA) manages a comprehensive network of meteorological observations that includes 77 weather stations, 57 web cameras and 6 visibility sensors spread throughout the country. Information is posted on the ICERA website, on variable message signs (VMS’s), the National Public Radio teletext and automated answering machines. In Finland, the Finnish Road Administration’s weather and driving condition monitoring system has been used to observe existing driving conditions for winter road maintenance, providing traffic information and implementing traffic management strategies. RWIS development began in 1975 and started national operation in early 1990's. Now it consists of about 400 road weather stations and over 350 cameras. Since winter 2009 about 100 new remote optical road surface state and friction sensors have been added to the system.

Weather and traffic information integration is a key requirement for WRTM and involves understanding how weather impacts traffic in the highway network, identifying high priority needs for weather information, and implementing selected integration strategies that bring the relevant information to bear on operational systems for managing traffic and informing the public. Traffic managers can effectively integrate weather information by: collecting, aggregating, analyzing, monitoring, and sharing traffic and road weather data collected from Environmental Sensor Stations (ESS) and other weather observing systems, installing high-speed communications, subscribing to value-added road weather forecast services, increasing technical and procedural connectivity; and using systems that support joint decision-making (5).

2.2 Traffic Modeling and Analysis

Many studies in the US and other countries have shown the impacts of weather on traffic, depending on the severity of rain, snow, or other conditions. In addition, researchers have already incorporated such weather impacts in analyses using traffic simulation modeling tools, such as DYNASMART, DynaMIT, AIMSUN, CORSIM, INTEGRATION, PARAMICS, VISSIM, and others. Adjustable weather factors allow these models and tools to simulate realistic traffic situations in inclement weather. Furthermore, weather databases provide adequate weather data to deploy the weather modules for traffic operations and management (6).

FHWA has been working with researchers and universities in the US and abroad to collect and analyze data and develop models and tools to improve the analysis, modeling and prediction of traffic flow in all types of weather conditions. Using data from Minneapolis-St. Paul, Seattle and Baltimore, FHWA conducted an empirical analysis of weather on traffic speed, capacity and density, documenting interesting results on the nature of speed and capacity reductions across the three metro areas as shown in Table 1 (7). No impacts were found on traffic stream jam density, but both rain and snow did impact traffic free-flow speed, speed-at-capacity and capacity, and parameters varied with precipitation intensity. Capacity did not vary with snow intensity, although capacity reductions of 12 to 20 percent were found in snowy conditions.
Similar studies in Europe have confirmed results obtained in the US. In Billot et al (8), the authors have analyzed a French two-lane interurban motorway. The main conclusion was that rain impacts the main macroscopic traffic characteristics. The fundamental relationship is affected and capacity decreases from 18.5% to 21% based on the intensity of rain, and free flow speed decreases by 8% to 12.6%. Similar to the FHWA results, rain has no impact on the jam density. Additional studies reported in (9) and (15) allowed us to highlight a European-US consensus about the effects of rain at a macroscopic level. Billot et al. (10) succeeded to establish a general framework for second order traffic models and also to incorporate weather information based on fundamental diagrams with different parameters, corresponding to different weather conditions. Traffic models of urban networks have also been studied as well as the dependencies on adverse weather conditions like rain and snow. Future work will focus on characterization of road links according to traffic parameters, both in normal and adverse weather (clustering maps). In addition to snowy road conditions and snowfall, saturation flow under (heavy) rainfall has to be investigated. More research will be devoted to multiple model filters, especially particle filters with models corresponding to variable conditions (rainy, icy, snowy, etc). The estimations tools developed in (10) and (15) have paved the way for integrating weather effects into decision support tools. Using Sequential Monte Carlo methods, ongoing research deals with a refinement of the tool with new features like online traffic parameters estimation and importance sampling. The validation with real-world data has already proved that this approach can bring many benefits to the road operators.

### TABLE 1 – Impacts of Precipitation on Traffic Flow in three US cities (Source: (7)).

<table>
<thead>
<tr>
<th>Traffic Parameter</th>
<th>Weather Condition</th>
<th>Range of Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-Flow Speed</td>
<td>• Light Rain (&lt;0.01 cm/h)</td>
<td>- 2 % to - 3.6%</td>
</tr>
<tr>
<td></td>
<td>• Rain (~1.6 cm/h)</td>
<td>- 6% to - 9%</td>
</tr>
<tr>
<td></td>
<td>• Light snow (&lt;0.01 cm/h)</td>
<td>- 5% to - 16%</td>
</tr>
<tr>
<td></td>
<td>• Snow (~0.3 cm/h)</td>
<td>-5% to - 19%</td>
</tr>
<tr>
<td>Speed at Capacity</td>
<td>• Light Rain (&lt;0.01 cm/h)</td>
<td>- 8% to - 10%</td>
</tr>
<tr>
<td></td>
<td>• Rain (~1.6 cm/h)</td>
<td>-8% to - 14%</td>
</tr>
<tr>
<td></td>
<td>• Light snow (&lt;0.01 cm/h)</td>
<td>- 5% to - 16%</td>
</tr>
<tr>
<td></td>
<td>• Snow (~0.3 cm/h)</td>
<td>-5% to - 19%</td>
</tr>
<tr>
<td>Capacity</td>
<td>• Light Rain (&lt;0.01 cm/h) and Rain (~1.6 cm/h)</td>
<td>- 10% to - 11%</td>
</tr>
<tr>
<td></td>
<td>• Light snow (&lt;0.01 cm/h)</td>
<td>- 12% to - 20%</td>
</tr>
</tbody>
</table>
Moving from macro to micro analysis, FHWA looked at individual driver responses to weather conditions, such as changing lanes, merging onto a freeway, making a left turn across traffic at an intersection, or adjusting the distance behind a lead vehicle. Using video data from intersections in Virginia and test tracks in Japan, the manner by which drivers perceive and accept gaps in traffic streams were analyzed and used to develop relationships that can support traffic signal phasing adjustments during weather events (11).

In France, all microscopic studies of loop detector data showed that drivers reduce their speeds under adverse weather conditions and increase their headways and spacing. In Billot et al (10), a drop of 18 % in time headway less than 2 seconds on the slow lane was observed as well as a decrease of 20 % of the spacing less than 160 feet. A log-normal distribution fit of the time headway distribution was achieved that highlights the differences according to the weather conditions. Similarly in Switzerland and Poland, analysis of headway data during various weather conditions showed that during good weather, more drivers maintain short headways compared to headways during low visibility and wet road surface conditions (see Figure 2).

![Headway distribution of free flow (500-600 vehicles/hr) under three weather conditions in Switzerland (one lane) (Source: (12))](image)

Future work in this area will focus on more detailed experimental work, data collection, and theoretical analysis of driver behavior in adverse weather. In addition, modeling of headway distribution that considers vehicle class, vehicle type, time of the day, and day of the week could provide more also step up this technique of determining traffic stability. These studies will be linked with different weather conditions, sensor data (e.g. from video cameras) and traffic data.

The goal of the above studies is to inform model development and decision support tools to allow a user to translate current and forecast conditions to traffic impacts. In addition to the macroscopic and macroscopic traffic flow research, the FHWA RWMP modified two Traffic...
Estimation and Prediction System (TrEPS) tools -- DYNASMART-P, a system for transportation planning, and DYNASMART-X, a real-time system for predicting traffic conditions and patterns -- to account for weather impacts, improving their traffic estimation and prediction capabilities and overall utility (13). These weather-sensitive TrEPS models have been calibrated and tested in four cities around the US.

2.3 Weather Responsive Traffic Management Strategies

Many transportation agencies in the US and abroad are incorporating road weather information, both current and predicted, in their traffic operation and management strategies. Current weather-responsive strategies range from advisory (alert and warning) systems to traffic signal control, all of which are used to facilitate travel in inclement weather. Advisory systems make drivers aware of current and impending weather and roadway conditions through passive and active warning systems, en-route weather alerts, pre-trip road condition information, and pavement condition information. In control strategies, traffic control devices including traffic lights/signals, ramp meters and dynamic message signs are modified during inclement weather by changing the interaction between detection systems and traffic control systems, implementing weather specific traffic signal timing plans, or programming weather-responsive ramp metering timing parameters. Traffic operation and management strategies that incorporate models and tools for weather responsive traffic analyses provide greater operational benefits.

In 2011, a comprehensive description of existing and improved WRTM strategies in the US was prepared by FHWA (14). The report details what strategies exist, where they have been used, the benefits realized, and how they can be implemented and evaluated. Table 2 shows a summary of major strategies being used, the weather conditions for which they apply, and the delivery or communication methods. In addition, five different WRTM strategy concepts of operations and high-level requirements were created as input to future system design. Guidance regarding evaluation approaches was developed to assist agencies in assessing the performance and benefits of WRTM strategies and systems.

<table>
<thead>
<tr>
<th>WRTM STRATEGIES</th>
<th>WEATHER CONDITIONS</th>
<th>DELIVERY METHODS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTORIST ADVISORY/WARNING SYSTEMS</td>
<td></td>
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<tr>
<td>Passive Warning Systems</td>
<td>Icy conditions, Wind</td>
<td>Static signs</td>
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<tr>
<td></td>
<td>Warning, Fog, Blowing</td>
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<td></td>
<td>Snow, Floods</td>
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<tr>
<td>Active Warning Systems</td>
<td>Icy conditions, Wind</td>
<td>Static Signs with</td>
</tr>
<tr>
<td></td>
<td>Warning, Fog, Blowing</td>
<td>Flashing beacons</td>
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<tr>
<td></td>
<td>Snow, Floods</td>
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<tr>
<td>Pre-Trip Road Condition Information and Forecast</td>
<td>Snow and Rain</td>
<td>511</td>
</tr>
<tr>
<td>Systems</td>
<td>Accumulations, High</td>
<td>Agency and private websites</td>
</tr>
<tr>
<td></td>
<td>Winds, Flooding, Limited</td>
<td>Media Outlets</td>
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<tr>
<td></td>
<td>Visibility, Tornados,</td>
<td>Text Messages</td>
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<td></td>
<td>Black Ice, Snow</td>
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</tbody>
</table>

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### En-Route Weather Alerts and Pavement Condition Information
Real-time information and alerts about specific weather and pavement conditions currently existing or developing ahead.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Social Networks (Twitter®)</th>
<th>Dynamic Message Signs (DMS)</th>
<th>Highway Advisory Radio (HAR)</th>
<th>511 FM/AM Radio</th>
<th>Text Message Alerts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulations, Flooding Snow and Rain</td>
<td></td>
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<tr>
<td>Accumulations, High Winds, Flooding, Limited Visibility, Tornadoes, Black Ice, Snow</td>
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<tr>
<td>Accumulations, Ponding, Flooding</td>
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</table>

### SPEED MANAGEMENT STRATEGIES

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Social Networks (Twitter®)</th>
<th>Dynamic Message Signs (DMS)</th>
<th>Highway Advisory Radio (HAR)</th>
<th>511 FM/AM Radio</th>
<th>Text Message Alerts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed Advisories</strong></td>
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<tr>
<td>Speed advisory messages are intended to achieve voluntary compliance with a recommended safe travel speed for the prevailing conditions. The speed advisory messages would not be considered enforceable by law enforcement personnel.</td>
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<tr>
<td><strong>Enforceable Speed Limits/Variable Speed Limits</strong></td>
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<tr>
<td>New speed limits or restrictions in response to weather conditions. Speed limits would be considered enforceable by law enforcement personnel.</td>
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</tbody>
</table>

### VEHICLE RESTRICTION STRATEGIES

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Social Networks (Twitter®)</th>
<th>Dynamic Message Signs (DMS)</th>
<th>Highway Advisory Radio (HAR)</th>
<th>511 FM/AM Radio</th>
<th>Text Message Alerts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size/Height/Weight/Profile Restrictions</strong></td>
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<tr>
<td>This strategy involves restricting specific types of vehicles from using the roadways during specific weather conditions. Vehicles may be restricted by size, height, weight, or profile based on weather conditions.</td>
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<tr>
<td><strong>Tire Chains/Alternate Traction Devices</strong></td>
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<tr>
<td>This strategy involves requiring vehicles to use special devices for improving traction between the vehicle and pavement. Using of traction control devices may be restricted to specific vehicles or may be required of all vehicles.</td>
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</table>

### TRAFFIC SIGNAL CONTROL

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Social Networks (Twitter®)</th>
<th>Dynamic Message Signs (DMS)</th>
<th>Highway Advisory Radio (HAR)</th>
<th>511 FM/AM Radio</th>
<th>Text Message Alerts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle Detector Configuration</strong></td>
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<tr>
<td>Reconfiguring detector settings or implementing special detector schemes/layouts to ensure detection of vehicles at traffic signals.</td>
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<tr>
<td><strong>Vehicle Clearance Intervals</strong></td>
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<tr>
<td>Altering the time duration of vehicle and pedestrian clearance intervals (i.e., yellow change interval, all-red interval, and pedestrian clearance interval)</td>
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<tr>
<td><strong>Interval and Phase Duration Settings</strong></td>
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<tr>
<td>Altering the time duration and/or sequencing of traffic</td>
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</tbody>
</table>

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signal phases to account for increases in start-up lost

time, reduced travel speeds, and reduced pavement
traction.

**Traffic Signal Coordination Plans**

New signal timing coordination plans designed to

improve progression and account for reductions in

travel speeds

**Ramp Control Signals/Ramp Metering**

Special timing plans to account for lost freeway
capacity, slow travel speeds, and increased start-up
time at ramp control signals

**ROAD RESTRICTION STRATEGIES**

**Lane-Use Restrictions**

Requiring specific vehicles to use specific lanes (e.g.,

trucks use right lane). May also include restricting the

use of special lanes by certain types of vehicle or all

vehicles (e.g., right lane closed ahead).

**Parking Restrictions**

Special parking restrictions or requirements in

response to developing or forecasted weather

conditions.

**Access Control and Facility Closures**

Controls that limit vehicle access to specific sections

of roadway. Access could be restricted to specific

structures (such as bridges, or causeways), passes,
or entire sections of roadway.

**Contraflow/Reversible Lane Operations**

Traffic is directed to travel in the direction opposite of

the normal flow. Generally reserved for large scale

evacuation, and where large volume of traffic needs
to be cleared for an area in a short time period.

<table>
<thead>
<tr>
<th></th>
<th>Rainfall, ice, limited visibility</th>
<th>Longer phase durations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain and snow accumulation, heavy rainfall, ice, limited visibility</td>
<td></td>
<td>Longer gap settings</td>
</tr>
<tr>
<td>Rain and snow accumulation, heavy rainfall, ice, limited visibility</td>
<td></td>
<td>Signal Timing Changes</td>
</tr>
<tr>
<td>Longer/shorter green times, Longer/shorter cycle lengths.</td>
<td></td>
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</tr>
</tbody>
</table>

**Motorist Advisory and Warning Systems**

In Finland, road users are provided with information on predicted road and weather conditions

via the internet, television and radio. This information is deemed valuable and useful as they

<table>
<thead>
<tr>
<th></th>
<th>Ice and Snow Accumulations, Rain, Flooding</th>
<th>Dynamic message signs (DMS), Static signs with variable message inserts Highway Advisory Radio Agency Websites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow Accumulations, Flooding</td>
<td></td>
<td>Static signs with variable message inserts Agency Websites</td>
</tr>
<tr>
<td>Snow and Ice Accumulation, Flooding, Limited Visibility, High winds</td>
<td>Dynamic message signs (DMS) Highway Advisory Radio, Access control gates Agency Websites Barricades On-Scene Personnel</td>
<td></td>
</tr>
<tr>
<td>Hurricane, flooding, developing major snow storms</td>
<td>Dynamic message signs (DMS) Static signs, Highway Advisory Radio, Access control gates/barricades, Traffic Signals, On-scene personnel</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2 – Summary of WRTM Strategies (Source: (14))**

Many of the strategies described in the FHWA report as being used in the US and listed in Table 2 are also being implemented in Europe as described below (15):
affect trip decisions. Pre-trip weather information improves road safety as drivers who received road weather conditions drove 3 mph slower than other drivers. In Iceland, the Road Administration provides forecasts using a small scale weather model on the web or via a phone hotline. In Denmark, a model for road surface temperature and sub-base frost depth prediction has been developed. The model is linked to a frost depth and sub-base temperature sensor and a weather station. Using input data from a five-day weather forecast, the model is capable of accurately predicting the development of freeze or thaw. The present condition of the roads is continuously reported on a map as well as forecasts for the next five hours. All information is available on the internet and as Apps for mobile phones. Statistics on use of the internet application prove significant interest for this information. On German motorways, precipitation and fog warnings are automatically generated while winter warnings of slippery and snowy roads are activated by the operator. Information and recommendations are communicated via VMS. Finnish studies showed that VMS warnings of slippery roads decreased mean speeds by around 1 mph when the signs were lit. Drivers’ anticipation of potential hazards makes them more cautious on the roads.

Speed Management Strategies

In Finland, on motorway E18, traffic is controlled by Variable Message Signs, combining variable speed limit and information text message signs. Four speeds limits, corresponding to four classes of road surface conditions (from very good to very bad), are defined. These classes are based on quantitative criteria addressing road surface conditions, wind, visibility, rain, ice, sleet or snow. Road surface condition class is estimated from different sources - road weather stations, cameras, data from police, road users input – which automatically sets the speed limit. An accident study showed that weather-related speed control reduced injury accidents by 13 percent in winter and 2 percent in summer.

2.4 Performance Measurement and Monitoring

A major barrier in adopting WRTM strategies is the lack of documented benefits to present a strong business case for transportation agencies to invest time and resources for implementation. Evaluation measures and procedures that meet the needs of the agencies and address national transportation goals are important for WRTM to become an integral part of agency operations. FHWA recently developed guidance as part of the comprehensive review of WRTM that describes a rational and practical approach to performance evaluation and benefits estimation for specific strategies. In addition to providing guidance for performance measurement, FHWA conducted a thorough self-assessment to measure progress towards program goals specified in highway legislation. The assessment identified meaningful, understandable, and practical measures to evaluate products and activities produced as part of the program.

Some of the WRTM benefits identified by the FHWA are (14):

- Fog warning systems have reduced crashes by 70 to 100%;
- Low visibility warning systems reduced speed variability by 22% and increased speeds by 11%; HAR messages helped Commercial Vehicle Operators (CVOs) make better route choices
Variable speed limits reduced average speed by 13%.

Weather-related signal timing reduced vehicle delay 8% and vehicle stops by more than 5%.

Weather and road condition information on websites lead to increased traveler satisfaction (94% reported being better prepared and 56% reported it helped avoid delays due to weather).

In Europe, although impact studies are rare, real-time information on slipperiness has reduced the risk of injury accidents in adverse conditions by 8 percent on main roads and 5 percent on minor roads (9) (12). Cooperative weather-responsive speed management systems can decrease fatalities by 3.5 percent with 50 percent compliance rate. Existing European field tests will provide more evidence on quantitative safety impacts of this information. The benefit-cost ratio of a weather-responsive, variable speed limit system is greater than one, at least for Finnish conditions. A decrease in costs for weather data collection and/or for information communication costs will contribute to the deployment of these systems.

In Germany, a variable speed limit system integrated with a fog warning system reduced the number of injury accidents on a motorway by around 20 percent. A Dutch fog warning system including a text warning and dynamic speed limit VMS signs on a motorway reduced speeds in fog by 5-6 mph, although in extremely dense fog, the system had an adverse effect on speed, because the “lowest possible speed limit” displayed in the VMS (60 kph or 38 mph) was too high.

2.5 Gaps and Opportunities in Current Approaches

As described above, significant research, development and deployment activities related to WRTM have taken place in the US and Europe, which demonstrate an advanced state of the practice in managing traffic under adverse weather conditions. However, some gaps and opportunities still remain. Recent advances in mobile sensing and data collection technologies for traffic and weather, including those coming from the Intelligent Transportation Systems (ITS) program, can help researchers and practitioners use more accurate, real-time and location-specific data to improve traffic analysis, modeling, forecasting and decision-making. For example, the Connected Vehicle Program’s Data Capture Management and Dynamic Mobility Applications capitalize on vehicle-infrastructure connectivity by using data from vehicle probes and other real-time data sources to enable TMCs to improve mobility and safety within and across modes more effectively while providing information to travelers to support dynamic decision-making.

There is also a need to develop and deploy advanced decision-support systems for traffic management similar to the Maintenance Decision Support System (MDSS), which is a tool originally developed by FHWA for winter road maintenance. Concepts of operations for advanced WRTM systems and strategies including Active Traffic Management, Traffic Signal Timing and Coordination and Traveler Information Systems were developed but need to be implemented and evaluated to demonstrate the benefits and provide guidance to agencies on how they can be successfully implemented.
Similarly in Europe, new research needs deal with the use of Advanced Driver Assistance Systems (ADAS), Cooperative Systems (V2I, V2V), Intelligent Speed Adaptation (for speed management) and Adaptive Cruise Control (for speed and headway management). Vision enhancements are the main research areas in ADAS for adverse weather conditions. The need to apply these systems increases with intensity of weather conditions. Existing traffic models should take into consideration the presence of vehicles equipped with ADAS. Traffic management and ADAS strategies have several common areas of research for improving traffic safety including collection and processing of road and vehicle performance data and identification of weather and traffic conditions. Traffic management strategies will improve with enhanced “Infrastructure to Vehicle” communications and information/knowledge exchange.

3. WRTM RESEARCH PROGRAMS

3.1 FHWA Road Weather Management Program

The US Federal Highway Administration (FHWA) Road Weather Management Program (RWMP)\(^1\) has been involved in research, development and deployment of strategies and tools for weather responsive traffic management. As a national champion dedicated to improving the safety, mobility and productivity of the nation's surface transportation modes by integrating meteorology into transportation operations and maintenance, the RWMP is meeting this challenge by studying, developing, demonstrating and implementing WRTM solutions. The impacts of these strategies on transportation operations include better or more informed decision-making by the agency and motorists, availability of real-time weather and traffic information, and improved mobility, safety and reliability of the transportation system during inclement weather.

The RWMP established a coordinated roadmap of programmatic initiatives in an effort to help state DOTs and affiliated agencies mitigate the adverse effects of weather\(^2\). The WRTM program brings together strategies, data and models, human factors, and system performance in a logical framework for action as presented in Figure 3. As described above, lots of research has been done on the various elements of the framework to understand the link between weather and traffic conditions, as well the benefits and impacts of WRTM strategies.

3.2 COST Traffic Management Program

COST is an acronym and intergovernmental framework for European Cooperation in Science and Technology, the oldest and widest European intergovernmental network for cooperative and coordinated research. COST has a very specific mission and goal, to reduce the fragmentation in European research investments and opening the European research area to worldwide cooperation. Founded in 1971, COST is presently used by the scientific communities of 35 European countries to cooperate common research projects supported by national funds\(^3\). With

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\(^1\) see http://ops.fhwa.dot.gov/weather/

\(^2\) see http://www.its.dot.gov/presentations/Road_Weather2012/Tuesday_Session1_Paul_Pisano_RWM_Program_files/frame.htm

\(^3\) see www.cost.esf.org
around €30 million of research funds per year, more than 30 000 European scientists are involved in research having a total value which exceeds €2 billion per year.

**FIGURE 3 – Framework for FHWA WRTM Research Program (Source: (4))**

Action TU0702 within COST is concerned with understanding the impacts of weather on freeways/motorways and urban highway network operations, and developing/implementing strategies to alleviate those impacts. This action brought together European researchers actively engaged in weather and road network management, focusing on mutually complementary methods for modeling, estimation and control to improve the safety and efficiency of traffic flow networks. COST researchers have formed an enthusiastic pan-European network of experts from 18 EU states and 2 non-EU countries, actively working on several aspects of RWIS (road weather information systems) and traffic management strategies during adverse weather conditions.

During four years of active international collaboration, COST Action TU0702 consisted of three working groups as follows:

1. Modeling Weather Impact on Traffic
2. Modeling Weather Impact on Road Surface and Pavement
3. Innovative Multi-sensor DF of Traffic and Weather Data

The major products from the working groups include two reports, namely (1) Effects of weather on traffic and pavement: State of the Art and Best Practices (12), and (2) Advances in modeling and weather-sensitive traffic management (15). The first report summarizes the activities of the working groups related to the state of the knowledge on adverse weather impacts. The other report contains advances in modeling and weather-sensitive traffic management that are expected to be very useful for adverse weather impact mitigation and road safety improvement. This report summarizes complementary methodologies for modeling, estimation and control of road network under adverse weather conditions. This interdisciplinary report contains detailed information for scientists and summaries dedicated to technical experts from road operators and traffic information centers. It also gives indications on open research questions in the field of adverse weather and transport networks.

3.3 Other Programs in the US and Europe

In the US and other countries, relevant research and development activities on WRTM components including traffic analysis and modeling, data collection and integration, human factors evaluation, performance measurement and the WRTM strategies themselves (advisory, control, treatment) have been performed by universities, transportation agencies and other public and private organizations. Extensive literature exists on the WRTM-related research results, decision-support tools and data that have been produced by such entities as State DOT’s, universities, Pooled Fund Programs like Aurora, TMC, Clear Roads and Enterprise, NCHRP, Strategic Highway Research Program, and PIARC, among others.

4. DEVELOPING A COMMON FRAMEWORK AND APPROACH FOR WRTM

4.1 Data Sharing and Knowledge Exchange

From the theoretical standpoint, all the questions about WRTM have not yet been answered and further research and development has to be done. In both the US and Europe, empirical studies about weather effects at both microscopic and macroscopic levels have to be completed. The major reason is that available studies do not cover the whole spectrum of weather events and driving environments. Although these completed research offer a first basis to integrate weather impact analysis and models into traffic management strategies, there is a need to share information and technologies, and compare world-wide knowledge and findings in order to obtain consensus and agreement about adverse weather effects. Such data sharing and knowledge exchange will also address differences in technologies, policies, environments and culture. A traffic-weather data exchange between Europe and the US would enable results consolidation and improved traffic models and strategies that will form the kernel of future decision support tools. Both sides have to think about common research frameworks and approaches for knowledge and data exchange, overcoming the traditional barriers such as privacy and communication constraints.
4.2 Research Partnership, Collaboration and Site Visits

While the FHWA Road Weather Management Program regularly partners with agencies and organizations in the US to conduct research and implement the WRTM elements of its program, it is important for the program to establish partnership and initiate collaboration with its international counterparts to leverage the knowledge and expertise of other countries that are dealing with the same problems and trying to achieve the same objectives. The COST group, as described above, presents an excellent opportunity for the RWMP to partner and collaborate with.

In Europe, the numbers of relevant ongoing projects are widely spread among countries but the research is fragmented and, in most cases, publication and distribution of most findings are at the national level only. Coordination at the European level has only recently emerged through such initiatives as COST Action TU0702. However, the importance of the coordination of research and development has been recognized and collaborative projects at European or even at international levels (mainly with Australia and Japan) are being set up. While this process is still ongoing, a next step could logically be to search for more collaboration in the field of weather effects on traffic operations with US and other parts of the world.

Another mechanism would be to organize technology exchange site visits between the US and European countries to promote the knowledge exchange between researchers and practitioners. Such visits could provide insightful views about what is a real weather-related traffic management situation and hence help researchers and practitioners understand and determine the appropriate tools and strategies for weather responsive traffic management. These visits can take place during international events like TRB Annual Meetings or ITS world congress.

5. CONCLUSIONS

This paper provides a general description of the state-of-the practice in weather-responsive traffic management in the US and Europe including the existing strategies and analytical tools used, their similarities, and their effectiveness in traffic operations. The paper also describes the relevant research activities that have been completed or are being undertaken in both continents and how the efforts can be coordinated and leveraged through data sharing, knowledge exchange and site visits. The paper also identified the gaps in current practices and research related to WRTM and provided recommendations on how those gaps can be filled. While much has been accomplished in the various areas that support the WRTM framework, significant gaps remain particularly in the areas of traffic modeling and impact analysis, and the application of mobile data and other advanced traffic and weather sensing technologies to support such analyses and traffic operation and management decision-making.

6. REFERENCES


