Operational Responses to Climate Change Impacts

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EXECUTIVE SUMMARY: HIGHWAY OPERATIONS AND CLIMATE CHANGE

Systems Operations and Management

Systems Operations and Management activities of transportation agencies-both state and local-have the objective of making the most effective use of the existing roadway capacity by improving efficiency (throughput, speed, safety), minimizing the service impacts of any disruption (crashes, weather), and providing special emergency services (evacuation). At the same time, maintaining and improving operational conditions has significant safety impacts, related both to roadway physical conditions (traction, visibility) and operating conditions (stop-and-go and tailback collision risks).

The ongoing transportation agency involvement in systems operations includes three basic streams of development:

- The gradually increasing commitment in many states to systematic congestion management–utilizing the evolving concepts and technology of freeway and arterial operations such as ramp metering, roadside variable message signs, speed and lane use controls, rapid clearance of crashes and breakdowns (including detours around problems), traveler information broadcast, and dial-up services.
- The routinized snow and ice control activities that already constitute a major and institutionalized maintenance responsibility in snowbelt regions.
- The clarification of transportation agencies' roles in supporting a more organized approach to emergency response–spurred by increased federal attention to standardizing preparation and response in natural disaster and security events in the post-9/11 and post-Katrina environment.

A key challenge facing the transportation community is combining these three streams of activity into an integrated all-hazard approach to accommodate the full range of incidents, hazards and emergencies and overcoming the current fragmentation among state and local transportation and public safety agencies. As climate-induced changes take place, weather is likely to play a larger role in this process

Weather Issues Within Systems Operations and Management

The impact of weather on transportation operations results from a range of well-known phenomena. Exhibit A indicates the principal impacts.

Serious weather events are already a major focus of highway operations. Weather-related events (rainfall, fog, blizzards, floods, sleet, snow, and ice) are significant disruptors of travel. Even minor events such as heavy rainfall reduce capacity and speeds and cause significant increases in crashes. Snow and ice, rain, and fog cause 15 percent of the total delay on the nation's highways–considerably more in some areas. Snow and ice control alone costs state DOTs about $2.5B–almost 40 percent of road operating costs. Many natural disasters (hurricanes, tornados and floods) have significant and long-lasting disruption impacts and emergency transportation response requirements. The population in potentially weather-vulnerable coastal areas is expected to increase in the next 20 years, from 35 million to 76 million.

<table>
<tr><th colspan="3">Exhibit A: Principal Climate Impacts on Operations</th></tr>
<tr><th>Climate-Related Road Weather Variables</th><th>Roadway Impacts</th><th>Operational Impacts</th></tr>
<tr><td>Air temperature and humidity</td><td>• Contribution to snow and icing
• Freeze/thaw cycle impacts on pavement smoothness</td><td>• Traffic speed</td></tr>
<tr><td>Wind speed</td><td>• Visibility
• Lane obstruction
• Major storm disruption
• Appurtenance damage
• Structural damage</td><td>• Travel speed and delay
• Accident risk
• Road closure</td></tr>
<tr><td>Rainfall</td><td>• Visibility distance
• Pavement friction
• Lane obstruction and submersion
• Landslides and scour
• Structural damage</td><td rowspan="2">• Roadway capacity
• Travel speed and delay
• Accident risk
• Road closure</td></tr>
<tr><td>Sleet/Snow</td><td>• Visibility distance
• Pavement friction
• Lane obstruction
• Avalanche risk
• Appurtenance damage</td></tr>
<tr><td>Fog</td><td>• Visibility distance</td><td>• Speed variance
• Travel time delay
• Accident risk</td></tr>
<tr><td>Sea level</td><td>• Lane submersion
• Structural damage</td><td>• Traffic speed
• Travel time delay
• Accident risk
• Road closure</td></tr>
</table>

Global Climate Change

Global climate change will influence the frequency, distribution and intensity of these events. These changes include:

- increase in temperature resulting in reduction in geographic coverage of major winter snowfall and conversion on possible increase in icing
- more intense major events and increased frequency (blizzards, hurricanes, tornados) in some regions already experiencing them and their direct impacts (flooding, scour, slides, operations interruptions) (these events also overlap with "natural disasters")
- more weather variation in places not previously experiencing it (major snowfall)
- modification of certain extensive climate conditions such as (continuing permanent) average temperature or average sea level and their direct impacts (permafrost melting, shorter seasons)

There are a range of studies that predict the temperature, weather and sea level implications of global climate change over the next century. The changes–on average– will be gradual across the US and therefore the changes in operational regimes in general will be responsive at an equivalent rate. However, a larger degree of variability and greater frequency of extreme events is also predicted–although not addressed in this paper–suggesting different levels of response in more affected areas. Exhibit B presents the general assumptions used in this paper.

Impacts of Climate Change and Needed Responses

The significant impacts of climate change are a long-run phenomenon and will be felt gradually over the next 50 to 100 years. During this period, a more affluent and time-sensitive society will expect to be provided with a highly reliable highway system. Transportation agencies, therefore, must continuously improve their capabilities to maintain service, minimize the impact of any disruptions–such as those related to weather–and to provide road-based emergency services.

Exhibit B: Climate Change-induced Weather Impacts

Weather Variables	Impacts	Exacerbated by
Temperature	General modest air temperature increases and consequent increase in border-line conditions (icing and slush)	Landscape and development
Rainfall	Increase in extreme events (rainfall and drought) with general increase in higher latitudes	Local drainage and Storm control
Sleet/snow	Reduced geographic coverage and duration in current snow areas with increases in certain locations not currently impacted	Increasing traffic and dependence on reliability
Ice	Reduction of overall extent but increases in freeze/thaw cycles incidence and extent	Increasing traffic and dependence on reliability
Hurricanes	Increase in incidence of level 3 and above	Increasing settlement in vulnerable areas
Seal level rise	higher sea-level, tides and surges	Increasing settlement in vulnerable areas

The impact of climate-induced weather changes on transportation on transportation policy and practice will depend on the how the changes are experienced. As suggested in Exhibit 11, the mix of changes in weather patterns will require a range of responses in operations technology, practice, programs, and institutional relationships.

With changes in frequency and distribution, "minor" weather events are likely to modify the inventory of incidents that will be part of routine operations–along with other traffic disruptions–as part of day-to-day traffic and incident management. At some point in this evolution, an increase in "weather event" frequency will become characteristic "climate" and the emergency response mode will no longer be efficient. At such a point, both technology and protocols (such as sensing, analysis, pretreatment, etc.) must become more routinized, rather than reactive, for an efficient response that minimizes disruption and more serious problems. Eventually, high frequency events may become a warrant for a design modification, rather than an operational condition, from a cost-effectiveness point of view. For example, regular flooding may suggest a design modification (improved drainage, elevated roadway) such that the weather event no longer requires and operational response.

With increases in intensity, more weather events are likely to be considered general emergencies (as they will have impacts beyond transportation). Even current best practice operational strategy in vulnerable areas may require upgrading. Prediction will become more important and, as the frequency of major storms increases, more routinized, suggesting the need for greater emphasis over time on prediction technology. (Exhibit C) Integrated responses will become more important and capital investments to support operations such as detection, surveillance, and message signs on evacuation routes will be required. For example, hurricane and flood evacuation routes and contra-flow infrastructure might become just as common as snow emergency routes in the upper Midwest and require design modification to handle new demands.

With changes in incidence, previously unaffected locations will gradually become subject to a new pattern of weather events. This may not require the development of new procedures or technology from an overall industry perspective, but it will involve the transfer of best practice to new locations. More widespread experience with new climate-induced weather patterns is also likely to increase the pressure to further routinize a more advanced state of the practice than is currently visible. A greater effort among transportation institutions–federal, state, local association and private–will be needed.

Exhibit C: Mainstreaming Climate Change in DOT Operations Regime

	Frequency: Institutionalization becomes Cost effective	
Intensity: Upgrade technology/procedures (Increase in threat levels)	Low frequency/High intensity • Prediction becomes important • Initiative new procedures • Introduce new technology	Moderate frequency/High intensity • Moves from operational to capital (risk-based in investment
	Low frequency/Moderate intensity • Consolidate into all-hazard for maximum efficiency using SOP	Moderate frequency/Moderate intensity • Consolidate into all-hazard for maximum efficiency using SOP • Threshold for extension of technology

As the 21st century proceeds, it may be expected that pressure from demanding constituencies will focus state and local transportation agencies increasingly towards real-time provision of real-time, delay-free service. A chain of related improvements in understanding, technology, protocols and institutions will be necessary. Improvements in *surveillance and monitoring* must exploit a range of potential weather-sensing resources – field, mobile and remote. With improved weather information, the more sophisticated, archival data and integration of macro and micro trends will enable regional agencies to *improve prediction* and prepare for long term trends. This in turn can support the development of effective *decision support technology* with analyses and related research on needed treatment and control approaches. The objective to be pursued would be road operational regimes for *special extreme weather-related strategie*s such as evacuation, detour, closings, or limitations based on *pre-programmed routines*, updated with *real-time information* on micro weather and traffic conditions. For such strategies to be fully effective improved *information dissemination* will be essential–both among agencies and with the public, using a variety of media. Finally, *the institutionalization* of the ability to conduct such advanced operations will depend on important changes in *transportation organization* and staff capacity as well as new more *integrated inter-agency relationships*

This is an ambitious agenda–but one that may become increasingly relevant as the climate-induced weather changes take place. In this new systems management and operations context, weather-related disruptions and emergencies will have become fully incorporated into systems operations and management.

I. HIGHWAY SYSTEM OPERATIONS AND MANAGEMENT TODAY

Systems Operations and Management activities of DOTs focus on making the most effective use of the existing roadway capacity by improving efficiency (throughput, speed, safety), minimizing the service impacts of any disruption, and providing special emergency services. At the same time, maintaining and improving operational conditions has significant safety impacts, related both to roadway physical conditions (traction, visibility) and operating conditions (stop-and-go and tailback collision risks).

State DOT and other major road-related entities involvement in systems operations includes three basic streams of activities:

- gradually increasing commitment in many states to systematic congestion management–utilizing the evolving concepts and technology of freeway and arterial operations and incident management, supported by intelligent transportation technology
- routinized snow and ice control activities that constitute a major and institutionalized responsibility of snowbelt states
- clarification of transportation agency roles in supporting a more organized approach to emergency response–spurred by increased federal attention to standardizing preparation and response in national disaster and security events in the post-9/11 and post-Katrina environment

Weather plays an obvious and major role in all of these activities. The US has a diverse climate ranging from subtropical to arctic and from arid to foggy, with several regions subject to extremes of temperature and events such as blizzards, hurricanes, tornados, floods, wildfires, avalanches, and slides. A broad range of the weather, temperature and sea level events are already experienced across the US.

Changes in climate-related conditions (temperature, wind, precipitation, sea level change) will impact the distribution, frequency and intensity of weather impacts within the DOT operational environment. As such changes will take place gradually over a long period of time, the implications of such changes must be judged by placing them in the context of the development and adoption of relevant practices as some extreme conditions spread or recede and others become more routine. Furthermore, as weather events are only one type of "incident" with which operations divisions are increasingly coping, the protocols, technologies and institutional relationships relevant to weather will be part of a larger context of evolution. This section provides this background as context to the potential impact of future climate-induced, weather-related impacts on transportation operations.

Weather and Causes of Delay

The highway network is increasingly congested. With growth in travel substantially outdistancing available highway capacity, substantial delays are routine and congestion is spreading over more areas and over greater numbers of hours. Congestion-related delay in the 75 largest metropolitan areas is estimated to cost over $72 billion per year in time and fuel costs.

Much of this delay results simply from demand in excess of highway capacity at peak periods. At the same time, however, today's high-volume highway level of service has made level of service more vulnerable to disruption from a variety of "incidents"–crashes and breakdowns, snow and ice, construction, natural disasters, and security-related measures. Highway service disruptions are becoming more frequent and long back-ups often accompany even modest incidents. Furthermore, such incidents are the major contributor to the lack of predictability and reliability of highway transportation service. Some incidents also involve significant impacts to life safety and responder safety, as well as property damage.

Exhibit 1 indicates that incident-related non-recurring causes contribute over 50 percent of the causes of urban highway delay–and even more in rural areas. Weather-related events contribute about 15 percent to this loss of capacity–including "routine" rain, snow and ice, and fog, as well as major weather events.

State DOTs and many local governments have long-standing programs to respond to major weather events–most notably routinized snow and ice control programs. In the 34 snow belt states, these programs represent a significant management commitment with well-organized components of weather tracking, pre-positioning of the workforce and equipment, and well-considered routines of treatment and clearance technology. Wisconsin, for example experiences 35-40 major storms per year. Snow and ice management are often the largest single budget "operations" budget item for such DOTs, and offer considerable political exposure.

Weather is also the major cause of natural disasters such as hurricanes, floods and tornados – events with consequences that place them on the agenda of state and local general-purpose governments. In these emergencies, state DOTs support established state and regional emergency response agencies, who in turn operate within an increasingly structured federal emergency framework. The increasing incidence of such events in recent years has called attention to the importance of the DOT's important transportation role in aspects such as evacuation and emergency access. The post-9/11 focus on terrorism threats and the appropriate public preparation and response–including the emergency support functions of DOTs–has added

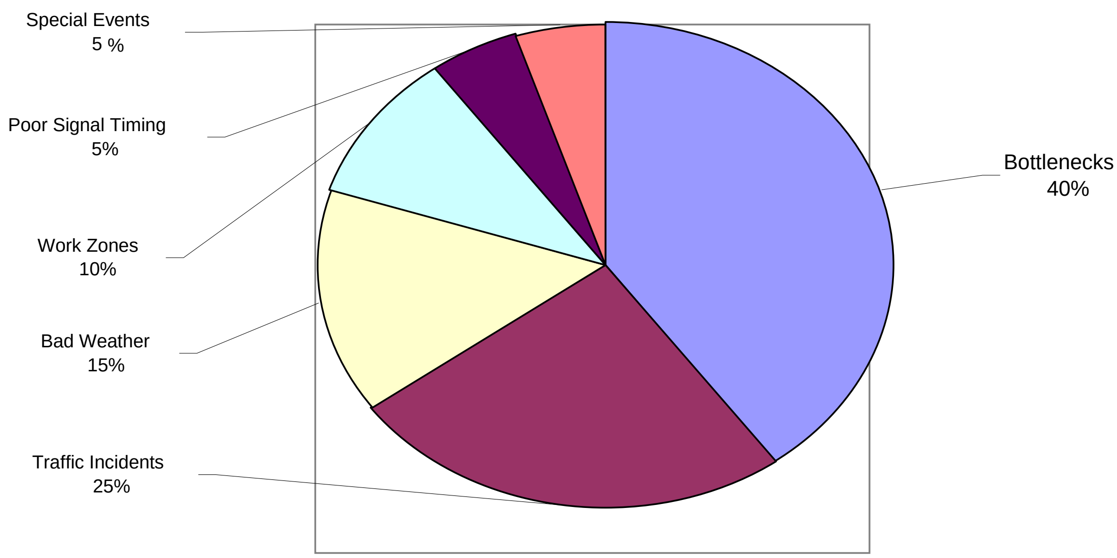


EXHIBIT 1 Sources of Delay and Unreliability
Source: *Traffic Congestion and Reliability*, FHWA, 2005

additional issues to the major incident operational agendas of DOTs. Emergency management as a function has become increasingly recognized in state DOT tables of organization and procedural routines.

Operations as a Response to Delay and Disruptions

State DOTs, larger local transportation agencies and authorities have only recently begun to organize towards a systematic response to the broad array of significant traffic disrupting incidents such as crashes and breakdowns via their regional traffic management programs and centers. Meanwhile, major weather related disruption–especially snow/ice management–is already well institutionalized in snow belt contexts via regional maintenance activities. Over a period of time, there will be a convergence of these trends: systems management will become more organized and comprehensive and weather will become more integrated into routine management. However, these trends will take some time–measured in decades. Formally organizing to prepare for and respond to routine incidents represents a substantial reorientation of the traditional state DOT mission. The pace of change is marked by the perception that providing new capacity ("building out of congestion") is increasingly costly and disruptive and involves long time cycles. Whereas the legacy engineering mission has long focused on the production of new capacity and its preservation, the systems operational mission involves improving the efficient operations of the existing highway system; i.e., maximizing the effective capacity and minimizing the impact of disruptions–both in the name of congestion management.

In concept, congestion management–with its 24/7 operational orientation–deals with both the daily and routine peak period congestion and with the less predictable disruptions of "incidents". A variety of concepts, systems and technologies are being applied to the existing highway network. These efforts include basic traffic engineering and application of intelligent systems (ITS) concepts and technologies in freeway and arterial operations, with such control strategies as ramp metering, dynamic message signs and traffic responsive signalization.

Given the substantial portion of delay due to non-recurring incidents, incident management is the core of operational activities that focuses on responding to disruptions to traffic flow that can include weather, as well as crashes and breakdowns.

Incident management routines have been improved through DOT provision of roving freeway service patrols and by closer cooperation in improved field procedures with public safety and emergency management agencies that have traffic incident command authority. Incident management includes all the activities involved in responding to the incident and returning to normal flow conditions. This includes removal of blocking vehicles, assurance of structural integrity of road infrastructure including emergency repairs, managing traffic flow during the incident (including establishment of detours), law enforcement, accident investigation, emergency medical response and hazardous material treatment. The establishment of regional traffic management centers (TMCs) as the state DOT "cockpit" for monitoring traffic incidents and providing police and DOT response and coordination of incident management and clearance is the most concrete expression of this growing commitment.

Most recently, as states develop their traffic and incident management program and, at the same time, participate aggressively in emergency response activities for natural disasters, there has been growing recognition of the natural overlap in appropriate preparations activities and response routines, as well as the commonality in technological support (such as communications and special equipment) and overlap in institutional roles and relationships–internal and external. These commonalities have been emphasized by regulations and best practices promulgated by the Federal Department of Homeland Security (DHS) as part of their focus on increased security.

As of today, the common threads among state DOT traffic and incident management and state DOT roles in emergency management can be characterized in three basic ways:

- an *activity environment* covering the procedures, processes, and roles used in the field to prepare for, and respond to both minor incidents and emergencies;
- an *institutional environment* addressing the policy framework, including legislation, policies, funding mechanisms, and interagency and public-private relationships; and
- a *technology environment* covering the equipment used to facilitate preparation and response – especially communications and information exchange.

While the ideal state of the practice is increasingly well understood, each of these developments is proceeding slowly–and at various rates–state by state.

State DOT Activity Environment

In the *activity environment*, the actual field activities in response to incidents or other emergencies take place within traditional frameworks designed to manage both generic traffic-related incidents and non-transportation emergencies (with transportation implications).

Real-time systems operations are organized at very different levels of formality across state DOTs. Most urban states have some kind of transportation management center as the information gathering and dispatching center for the DOT role is in incident and emergency response. The TMC is the location of communications and controls for freeway and arterial traffic management systems, such as ramp meters and DMS and public information networks.

Incident management is an important part of systems operations. While state DOTs are not in the jurisdictional lead for traffic incidents, they are often directly involved in incident detection, surveillance, dispatching, and traffic control–working more or less closely with local PSAs such as law enforcement and fire and emergency services. "Incidents" are detected from DOTs' road-based detection and surveillance technology, bystander cellphone or roving police and DOT service patrol vehicles. Both PSA dispatch centers and state DOT TMCs may then be involved in dispatching appropriate equipment for response and providing support to PSA and DOT personnel in the field in incident clearance. The field activities of clearing the incident and managing the traffic are a cooperative effort, *per se*, with procedures and protocols gradually being defined across the DOT and police cultures.

The effectiveness of these systems operations–especially those related to incident management–varies widely, depending on the amount and quality of surveillance and detection systems deployed, the operational regimes employed by the DOTs at the TMCs, and sharing responsibility for the incident command and related protocols for the on-the-ground activities of DOT and PSA personnel.

Within this overall context, the importance of these weather-related disruptions with respect to day-to-day highway management response varies with their frequency and intensity as they occur state-by-state around the US. For example, significant improvements have been made in some areas regarding response to major weather events, such as snow/ice storms and hurricanes.

- Snowbelt transportation agencies have highly institutionalized snow and ice control programs with separate budgets, clear lines of responsibility, staff roles, equipment inventories, control practices, and public information programs. Individually and in consortia states have developed increasingly sophisticated road weather information systems integrating environmental sensors at various scales with prediction and information dissemination. Advanced treatment routines have also been developed.
- States subject to severe tropical storms have well-developed hurricane procedures, varying with anticipated threat level, in which state DOTs play a significant role–as is also the case in tornado-prone settings. For example, the institutionalization of evacuation procedures (including measures such as contra-flow lanes) represents a response to the increased frequency of hurricanes in the Gulf and higher standards of risk management.

By contrast, other states not directly in the Snowbelt or storm track may also experience these weather events–but they are treated as special events with preparation level depending on the likely degree of risk presented.

By contrast with traffic incident management and snow and ice control, emergency management has a different place organizationally within state DOTs, focusing on responding with certain emergency support functions related to transportation and public works upon request from state and regional emergency management agencies. The DOTs have certain standardized call-out procedures and functions, as requested from state and regional commend centers that can relate to helping law enforcement with detours, quarantines, emergency access, repairs, supply of special equipment, etc. States with a high level of exposure to specific natural disasters have developed special protocols that are often embodied as annexes to existing formal emergency response plans. Some of these protocols focus on disaster-specific transportation operations procedures, such as designated evacuation routes and evacuation procedures, signage and roadway engineering, contra-flow lanes, public information, rapid incident clearance on evacuation or emergency routes, and coordination across all transportation modes.

Weather-related events (rain, snow and ice, high winds, flooding) are subject to a fuzzy boundary as to whether they should be treated as transportation incidents (with DOTs in the lead) or should become declared emergencies with state and regional emergency management agencies taking the lead with DOT and other agencies' support. Many of the same functions and capabilities and technologies, staff management and relationships are involved in the state DOT transportation emergency support functions (ESF). In any case, it is apparent that historically there is considerable duplication of the responsibilities and activities cutting across routine (but real-time) traffic operations, traffic incident management (including weather events), and the procedures protocols, systems and relationship needed for emergency management. Typically these three activities have tended to be stovepiped within state DOTs and without formal and budgeted program recognition. However, as more attention is given to emergencies, and as the standards of performance for traffic incident management have become more stringent, best practices are being identified and moves are being made to organize incident and emergency response more explicitly within state DOTs.

Considerable momentum has been led to these developments by the response to 9/11 and Katrina. With the formation of DHS, the federal government is moving to standardized "incident response" (referring to the complete range of disruptions) based on an all-hazard approach–covering terrorism, natural disasters, health, industrial accidents and transportation incidents. DHS has promulgated the National Incident Management System (NIMS), which recognizes the differing characteristics and dynamics of various incidents and emergencies, and provides a standardized phased approach to incident planning, preparation and response, together with a set of specific procedures focused on improving the ability of state and regional responders (recipients of federal emergency preparation aid) to respond to a broad array of natural, security, industrial and health threats. The DHS National Response Plan structures the operational response to incidents and events into several generic phases:

- awareness (monitoring and prediction)
- protection (where relevant)
- preparation
- response
- recovery.

Within each of these phases there are certain characteristic activities related to any threat to highway operations continuity–including those that are weather-, temperature- and sea-level-related. Each of these activities has a current state-of-the-practice that has typically been focused around a particular hazard–major crashes, major weather events, natural disasters, or terrorism attacks.

Technology Environment

Within the transportation operations arena, significant advances have been made in technology, particularly in the application of Intelligent Transportation Systems (ITS). Surveillance, communications, processing, and information dissemination technologies now enable the collection of information on traffic flow and roadway performance and enable operators to monitor conditions (in real time) of the roadway, railways, ports, and throughout transit systems. Detection subsystems may collect data (volumes, speeds, and travel times), locate vehicles, or provide video images. Sensor technology enables the monitoring of roadway, railway, and environmental conditions. Collected data feeds the management and information dissemination functions, and enable operators to appropriately intervene in those functions. The data may be stored (warehoused) for future analysis and performance evaluations. These resources have significant potential in an emergency response context, beyond their intended traffic management purposes. The value of this potential is becoming more clear to other state agencies, and the co-location of statewide or regional transportation management centers (TMCs) and emergency management centers is gaining in popularity.

The technology of ITS includes both fixed and movable traffic devices that–in combination–can be deployed to provide control and advisories on a flexible geographic basis as incidents of events warrants. These include environmental and traffic sensors, variable message signs for warnings and detours, gates for lane closings and automated ramp controls.

Weather is an integral part of the National ITS Architecture, with most elements designed to transmit weather-related data for use in traffic control, treatment and other maintenance areas. Road weather data comprise one category of input into decisions about traffic control and motorist warnings. ITS control elements include:

- Advanced traffic signal control systems to modify traffic signal timing based upon pavement conditions
- Variable Speed Limit (VSL) signs and Dynamic Message Signs (DMS) based upon visibility, pavement, traffic, and/or vehicle classification data to modify speed and flow
- Automated ramp gates, lane use control signs, flashing beacons, Highway Advisory Radio (HAR), and DMS can be employed to alert motorists of weather-related hazards and access restrictions to affected bridges, specific lanes, entire road segments, or designated vehicle types (e.g., high-profile vehicles)

The deployment of 511 telephone travel information services in many areas of the United States has focused on communicating weather-related road conditions to travelers during the winter months. A number of states have also made Road Weather Information Systems (RWIS) information available on web sites, often in coordination with traffic and other traveler information.

Another important attribute of ITS, critical for emergency response, is "regional integration." The responsibilities for managing and operating surface transportation networks are shared by many entities. Most significantly, state and local DOTs, transit agencies, toll and tunnel/bridge authorities, ports and intermodal facilities, and (in some cases) private information service providers (ISPs) are responsible for gathering the necessary information. These entities are not only information gatherers, but users, along with other entities and stakeholders (e.g., FHWA, Federal Transit Administration (FTA) , Federal Emergency Management Agency, emergency service providers, law enforcement, Metropolitan Planning Organizations (MPOs), private sector independent service providers (ISPs), and even automotive manufacturers). Therefore, it is critical that collected information is shared in real time to create a region-wide integrated database.

The need for interoperable interagency communications is widely acknowledged but represents an expensive challenge in many regions – especially for the PSA community. More generally, information-sharing protocols for each significantly different emergency type (e.g., weather, security, planned event) are not uniformly developed and often involve different units within responder agencies. The recent problems associated with state and local coordination exhibited in the Gulf hurricanes illustrate some challenges in that area. While the National ITS Architecture has added Disaster Response and an Emergency Evacuation User Service theoretical framework has been established (Exhibit 2), implementation is occurring slowly.

The TMCs established by state DOTs offer capabilities in surveillance and communications that are not widely appreciated or exploited by the general emergency management community. For example, TMC dispatch integration benefits may be obvious, but few regions are progressing in this area. Information sharing between DOT staff working in traffic centers and emergency response agencies requires improvement. Motorist information devices that can be utilized in a wide range of emergencies (but are not yet effectively used from either timeliness or information perspectives) are available.

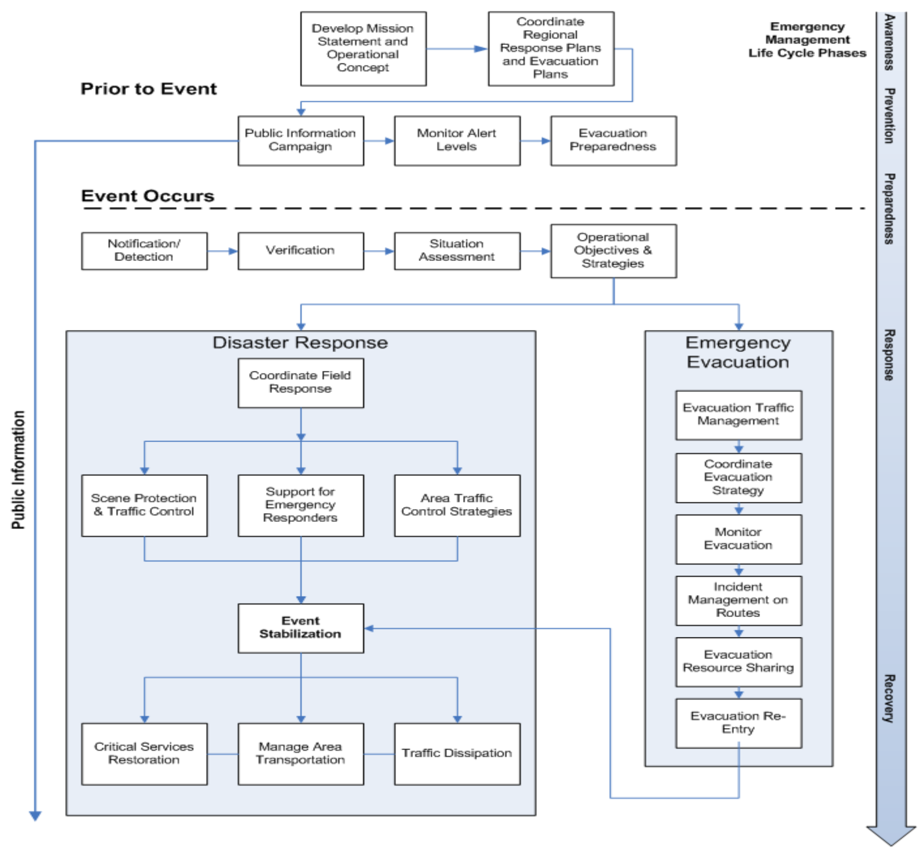


EXHIBIT 2 ITS National Architecture User Service for Disaster Response Evacuation
Source: http://www.its.dot.gov/arch/archnew_dsastr.htm#_Toc46037009

Institutional Environment

Perhaps the greatest challenges to enhanced emergency response capabilities and emergency transportation operations (ETO) are found in the institutional environment. As suggested by Exhibit 3, the number of institutional players tends to increase with the scale of the emergency. At the same time, however, the objectives, priorities, and management style exhibited by the key stakeholders (police, emergency medical services, fire and rescue, DOTs) in both conventional traffic incidents and in non-transportation-generated emergencies, based in law, culture, and resources, are somewhat different.

In addition, the legal and regulatory environment also varies substantially by state. In particular, the DOT emphasis on maintaining and restoring transportation service needs to be well-integrated into the emergency management procedures of partner agencies.

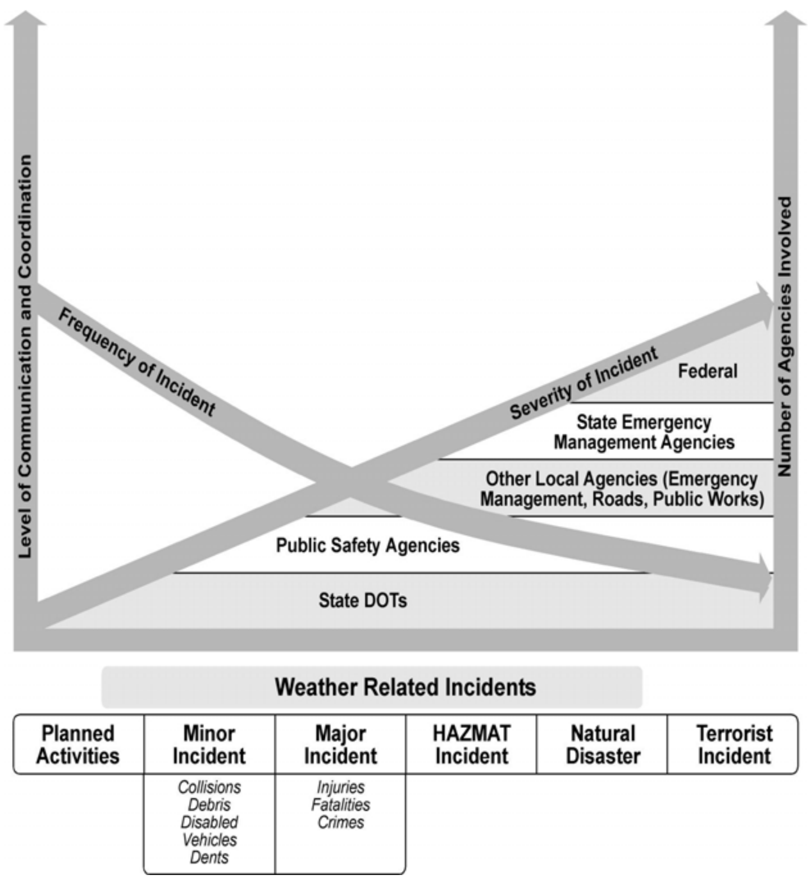


EXHIBIT 3 Incident Complexity
Source: *Project 20-59(11) Guide for Emergency Transportation Operations, 2004, PB Consult*

Real-time systems operations is not typically treated as a formal, budgeted, managed program in most state DOTs. As suggested above, the various dimensions tend to be fragmented, part-time reactive activities, with responsibilities divided among maintenance, traffic operations units, TMC management, ITS project staff and designated emergency managements. Key challenges include the following:

- Some of the key components (e.g., ITS, service patrols, communications) do not compete well for resources, and there is no clear professional cadre of related technical certification devoted to incident and emergency management. By contrast, the DOT commitment to snow and ice control suggests the potential of an organized, institutionalized approach.
- State DOT relationships with public safety agencies vary widely. The strongest relationships are in the field, where there is often a high degree of cooperation, informal communication, and respect. However, formal inter-institutional relationships on an ongoing basis remain the exception.
- The need for improved training, both on an inter- and intra-agency basis for standard incident and emergency response and for specific incident types–such as those related to weather.
- There are differences in the degree of formality in emergency management planning and activities imposed on state DOTs by the federal and state emergency management framework. Nationwide, there are still few formal interagency agreements on policy, procedures, or performance tracking, although the NIMS consistency requirements will have an impact.
- There is considerable room for improving the relationships among the producers and users of weather-related information affecting transportation service. This includes federal and federal-state levels between and among the weather- and transportation-related entities–public and private–including the USDOT, the National Weather service, the state DOTs (including the American Association of State Highway and Transportation Officials (AASHTO), various multi-state coalitions with shared weather interests, private industry weather information analysts and vendors, and the range of transportation users. As described below, these relationships are gradually being built into integrated coalitions with a focus on research and dissemination.

In this setting, weather and climate issues are an underlying, crosscutting influence that determines the state's approach to operations, ranging from the most routine response (in traffic management) to major emergencies. Any major change, either in the policy toward weather impacts or in weather itself, will have a broad impact that may help knit together the current strands of operational management.

II. THE IMPACT OF CURRENT CLIMATE ON TRANSPORTATION OPERATIONS

As described above, weather is one of many disruptions confronting transportation operations. The future impact of climate-induced changes must be understood within the framework of how current climate-related conditions (temperature, wind, precipitation, sea level change) affect transportation.

Direct Impacts of Weather on Transportation Operations

The impact of weather on transportation operations results from a range of well-known phenomena. Exhibit 4 indicates principal impacts–presented in greater detail in Appendix A–which include:

- Decreased pavement friction affecting vehicle performance, including traction and maneuverability, resulting in loss of control and skidding;
- Reduced roadway capacity because of slower speeds, particularly on grades and horizontal and vertical curves, and at intersections;
- Limitations on visibility because of precipitation and windshield obstruction;
- Lower travel speeds and greater speed variability resulting from differing driving habits and abilities;
- Periodic lane obstruction because of ice accumulation or closures for roadway treatment; and
- Disrupted bus transit schedules because of variable operating conditions.

Climate-Related Road Weather Variables	Roadway Impacts	Operational Impacts
Air temperature and humidity	• Contribution to snow and icing • Freeze/thaw cycle impacts on pavement smoothness	• Traffic speed
Wind speed	• Visibility • Lane obstruction • Major storm disruption • Appurtenance damage • Structural damage	• Travel speed and delay • Accident risk • Road closure
Rainfall	• Visibility distance • Pavement friction • Lane obstruction and submersion • Landslides and scour • Structural damage	• Roadway capacity • Travel speed and delay • Accident risk • Road closure
Sleet/snow	• Visibility distance • Pavement friction • Lane obstruction • Avalanche risk • Appurtenance damage	
Fog	• Visibility distance	• Speed variance • Travel time delay • Accident risk
Sea level	• Lane submersion • Structural damage	• Traffic speed • Travel time delay • Accident risk • Road closure

EXHIBIT 4 Principal Climate Impacts on Operations

Source: adapted from *The Potential Impacts of climate change on Transportation, USDOT, 2002*

Weather Incidence

The types of changes summarized above are expected to take place gradually, over the next 50 to 100 years. While the magnitude of these changes may appear modest, from an operations point of view, they must be considered in light of the current exposure of state DOTs to potentially disruptive weather and temperature events.

The US already has a diverse climate ranging from subtropical to arctic and from arid to foggy, with several regions subject to extremes of temperature and events such as blizzards, hurricanes, tornados and floods, wildfires, mudslides and avalanches. Most of the weather-, temperature- and sea-level-increase-induced impacts of global climate change, in terms of level, frequency and intensity, are already experienced somewhere in the US.

Already today over 70 percent of the nation's roads are in snowy areas. Snow and ice, rain and fog cause 15 percent of the total delay on the nation's highways. Snow and ice control costs state DOTs about $2.5B–almost 40 percent of road operating costs. Over half of the US population has a least a five percent chance of experiencing a hurricane of the scale of Katrina. Prior to Katrina, 60% of hurricane deaths were due to drowning in vehicles. The population in potentially weather-vulnerable coastal areas is expected to increase in the next 20 years, from 35 million to 76 million.

Impacts on Level of Service

These impacts, taken together, have significant effects on level of service and safety. Exhibit A in Section I indicated the contribution of weather to total delay. Within the group of causes of non-recurring congestion–those causes that are the principal focus of systems operations and management–weather contributes about 10-15 percent of the total delay. These aggregate figures hide the variable impacts that weather can have in various specific contexts. The FHWA reports a range of impacts.[1]

- On freeways, light rain or snow can reduce traffic speed by roughly 10 percent. Heavy rain can decrease highway speeds by approximately 16 percent. In heavy snow, freeway speeds can decline by about 40 percent.
- It has been estimated that 23 percent of the non-recurrent delay on highways across the nation is due to snow, ice and fog. This amounts to an estimated 544 million vehicle-hours of delay per year. Region-specific studies have shown that during adverse weather, average travel time delay increases by 14 percent in Washington, D.C. and by 21 percent in Seattle, WA.
- On signalized arterial routes, the delay impacts are even greater, with speed reductions from 10 to 25 percent on wet pavement and from 30 to 40 percent with snowy or slushy pavement. Arterial traffic volumes can decrease by 6 to 30 percent, depending on road weather conditions and time of day. Travel time delay on arterials can increase by 11 to 50 percent, depending on severity of the weather event.
- Capacity reductions can also be caused by lane submersion due to flooding and by lane obstruction due to snow accumulation and wind-blown debris. Road closures and access restrictions due to hazardous conditions (e.g., large trucks in high winds) also decrease roadway capacity.

[1] FHWA Road Weather Management Program: http://ops.fhwa.dot.gov/Weather/q1_roadimpact.htm

Impacts on Safety

Safety impacts are also significant. Each year over 17 percent of fatal crashes, 22 percent of injury crashes, and 25 percent of property-damage-only crashes occur in the presence of adverse weather or slick pavement. Exhibit 5 indicates National Highway Traffic Safety Administration (NHTSA) estimates of the association of weather conditions with crashes.

Overall, it has been estimated that weather-related crashes (rain, sleet, fog, snow and ice) are responsible for nearly 7,400 of the 41,000 annual highway fatalities, plus over 690,000 injury crashes. This represents over one-quarter of the total crashes and almost 20 percent of the fatalities. Together with property damages, this is estimated to have an economic value of over $40 billion.[2]

Importantly, these statistics tend to understate the impact of weather on delay and crashes, since bad weather often occurs in combination with other road service disruptions, such as congested stop-and-go traffic conditions or the operational disruptions caused by road work zones. While there is no research on the net impact of combined conditions, analysis of the occurrence of combined conditions suggests the relevance of this consideration.

Economic Implications of Current Weather

These reductions in level of service and safety have important economic impacts. First, they increase the operating and maintenance cost of state DOTs, PSAs and emergency management agencies. Winter road maintenance accounts for roughly one-quarter of state DOT maintenance budgets, amounting to over $2.3 billion -- plus over five billion dollars to repair infrastructure damage caused by snow and ice.[3]

In addition, productivity losses are reflected in the loss of trucking of an estimated 32.6 billion vehicle hours ($2 billion to $3 billion in economic value) due to weather-related congestion in the nation's 281 largest metropolitan areas.[4]

Conditions	Percent of Weather related Crashes
Wet pavement	76%
Rainfall	48%
Snow or sleet	14%
Icy pavement	13%
Snowy or slushy pavement	10%
Fog	3%

EXHIBIT 5 Causes of Weather-Related Crashes
Source: *NHTSA data analyzed by Mitretek Systems*

[2] *Lombardo L, ,Overview of US Crashes and Environment, 2000*
[3] *FHWA: http://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm*
[4] *Analysis of Weather Incident Effects on Commercial Vehicle Mobility in Large U.S. Cities, Mitretek Systems*]

III. FUTURE CLIMATE CHANGE-INDUCED IMPACTS ON WEATHER

In considering the potential ramifications regarding highway operations response to climate change, a scaling of the level and location of change is required to set the framework.

Future Changes in Climate

There are a range of studies that predict the temperature, weather and sea level implications of global climate change over the next century. Details and differences regarding their dynamics and probability are critical to individual states–but not germane to the considerations of this paper, since the changes are gradual–and changes in operational regimes will be responsive to changes at a more general level. Therefore, certain general assumptions have been made, summarized in Exhibit 6. These include:

- General air temperature increase of three to four degrees, including the most significant winter warming in more northwestern states and the most significant summer warming in New England and the Western states
- Change in snow and ice patterns, including a general increase in freezing precipitation over the Midwest and reduced snow level in the Southeast and lower Great Plains, heavy but episodic storms in the Midwest and East

	Current Conditions	Climate Change-induced Impacts	Exacerbated by:
Temperature	Occasional cold or hot spells	General modest air temperature increases and consequent increase in border-line conditions (icing and slush)	Landscape and development
Rainfall	Periodic low rainfall Occasional wet spells	Increase in extreme events (rainfall and drought) with general increase in higher latitudes	Local drainage and storm control
Sleet/snow	Snow requiring real-time treatment to maintain service	Reduced geographic coverage and duration in current snow areas with increases in certain locations not currently impacted	Increasing traffic and dependence on reliability
Ice	Ice conditions	Reduction of overall extent but increases in freeze/thaw cycles incidence and extent	Increasing traffic and dependence on reliability
Hurricanes	Occasional seasonal hurricanes Level 3 or below	Increase in incidence of level 3 and above	Increasing settlement in vulnerable areas
Sea level rise	Coastal surges with hurricanes and high tides	Higher sea-level, tides and surges	Increasing settlement in vulnerable areas

EXHIBIT 6 Climate Change Induced Impacts

Source: *The Potential Impacts of Climate Change on Transportation, USDOT 2002; Where the Weather Meets the Road, NRC, 2004*

- Warming temperatures in general increasing the freeze-thaw cycle frequency in very northern states–especially Alaska
- Generally longer and more intense thunderstorm season in the Southeast and Midwest
- Increased number of higher intensity Gulf hurricanes
- Sea level increases in the Gulf and mid-Atlantic of one to three feet
- Increase in the incidence of floods, wildfires, avalanches and slides caused by the changes in rainfall and increase in temperature variability

Impact Implications

The combination of the changes in the frequency, intensity and incidence of weather changes in combination with the changes in context suggests a set of implications for transportation operations. This will include:

- While temperature increases will reduce the geographic areas affected by major snow events, there will be more intense major events (blizzards and hurricanes) in some regions already experiencing them. Precipitation impacts, especially snow- and ice-related events, given the extent of coverage, will continue to present the greatest safety, property damage and maintenance problems–and the greatest expenditure impacts on state DOTs. However, there will also be an increase in the impacts of other storm events (inland and coastal flooding, scour, avalanches, slides) and the need to scale up and tailor response-related preparations, including longer lead times. More weather events are likely to fall into the full emergency category.
- Greater frequency and incidence of such major events and weather-induced impacts (floods, avalanches, slides), suggesting the spread of standardized procedures and the potential of investments in "permanent" infrastructure and suitable routine mainstreaming.
- Greater frequency and variability of modest–but disruptive–weather events (thunderstorms and general rain and snowfall), suggesting recurring weather-related traffic disruption in a shorter time as a more significant incident for focus of routine management.
- Temperature increases will have a major impact on maintenance, although they will also influence the design of snow and ice treatment options.
- More weather variation in places not previously experiencing it (major snowfall), implying the involvement of previously unaffected states and the adoption of proven approaches among peer states.
- Modification of certain extensive climate conditions, such as (continuing permanent) average temperature or average sea level and their direct impacts (permafrost melting, shorter seasons) with implications for adjustments in the physical infrastructure itself to minimize impacts (such as pavement design, drainage, stormwater management, etc.).

Context and Expectations

The significance of the small climate-induced changes is greater than the small statistical shifts in temperature, precipitation and sea-level might at first suggest. First, the nature of these challenges will be affected by other context changes taking place over the same time period for which climate change impacts are forecast (50-100 years).

Exposure

A larger population will be exposed to the implications of temperature and weather events. These changes will include:

- Anticipated growth in travel–perhaps doubling in 30 to 40 years
- Substantial increase in exposed populations–especially in coastal areas and recreation and second home settings
- Increases in the importance to the economy of just-in-time highway transportation reliability.

Public Expectations

At the same time, there will be higher public expectations regarding public service levels of service and responsiveness, since other aspects of transportation service will have improved substantially. This level of information and awareness will produce a high level of expectations and accountability well beyond today's norm for incident and emergency response. For example:

- The combination of advanced vehicle-roadside communications will support high-resolution travel conditions information. This, in turn, will support higher standards regarding incident and emergency response regarding notification, travel advisories and supply of alternative routing/strategies.
- Public expectations regarding more stringent life safety protection standards and measures will be continually increasing, despite the tendency to risk higher exposure in settlement patterns, transportation and related activities.
- Expectations of reliable service will become more stringent–especially as tolled and priced roadways become more common.

Evolution of Institutions

Transportation institutions and their capacities will concurrently be evolving in two relevant directions:

- Ability to capitalize on advanced technology to improve operations, including communications, control and analytics (computation)
- Realigned and consolidated jurisdictional missions and structures regarding transportation systems provision, operations and management.

IV. IMPLICATIONS OF FUTURE CLIMATE ON OPERATIONS

The climate change described in the previous section will take place over an extended time period and on a gradual basis, measured in terms of decades. At the same time, transportation operations, as a discipline, is in its infancy and developing slowly in response to a range of driving forces for improved operations–of which climate-related weather impacts is only one.

In the section below, key directions of change that will improve overall systems operations are identified. An appropriate response to the weather impacts of climate change is an integral part of many of these changes–although weather is only one of many driving forces. Many of the needed improvements in agency practice are recognized within the professional leadership of the transportation community–but face difficult institutional challenges associated with competition for management attention and resources as well as the need to coordinate across institutional boundaries. The trends and developments are discussed with an emphasis on state DOTs and their special relationship with FHWA. However, all the issues that pertain to state DOTs also pertain to any of the larger road-oriented transportation owner-operators such as local governments and authorities

Short Term Development

In the short run (10-20 years), the impacts of climate change will be modest. Emphasis is likely to be on improving existing operations to respond to the full range of incidents and emergencies, of which weather is only a part. Key driving forces will include:

- the increasing economic value of highway travel–both passenger and goods–resulting in a heightened policy imperative of maintaining day-to-day highway level of service in the face of the changing pattern of "regular and routine" temperature-, weather- and sea-level-related disruptions, combined with the increase in the exposed population in weather-subject areas
- expectations that best available all-hazard traffic/emergency operations practice will be adopted on a widespread basis
- improved practice in all phases of operations based on new detection, prediction, communications and control/treatment systems and technology

The substantial gap between the state of the art and the general state of practice suggests that a major emphasis needs to be placed on "mainstreaming operations"–full deployment of available ITS infrastructure, adoption of improved traffic management, incident management and emergency operations practices and their integration within the state DOT organizational environment.

Mainstreaming Operations as a Context for Improved Weather-Responsiveness

Developing improved operational response to climate-change-driven weather events that affect transportation level of service–or require special transportation support–must take place within the overall state DOT context for systems operations and management. As described in Section II, this context still varies widely among states, but remains today substantially *ad hoc*, reactive, informal, and unprogrammed. Improving routine road weather management and weather-related emergency response is dependent on progress in formalizing and improving transportation operations as a whole. There are several key context dimensions currently under discussion within the state DOT community that indicate a growing consensus around areas where progress is essential.[5] The recommended strategies for mainstreaming operations include:

[5] *Project 20-59(11) Guide for Emergency Transportation Operations, 2004, PB Consult*

- *Adoption of an integrated, all-emergency/hazard approach for systems operations* – Proactive anticipation of common and unique hazards and development of hazard-specific protocols and technology are key to improving the safety of those involved in and responding to incidents. Useful features are incorporated from preparation and response requirements to the complete range of special events and emergencies.
- *Development of a structured transportation incident and emergency operations process with joint interagency protocols and procedure.* – There appears to be significant efficiency and other benefits from combining the best practices from traffic incident management and the range of emergency transportation operations into a single comprehensive framework that can be organized, managed, and improved. The state DOTs (and local government transportation entities) and public safety agencies have different but overlapping objectives that must be accommodated. Exhibit 7 suggests that best practice in Emergency Transportation Operations (ETO) as being developed within the highway community is significantly consistent with the priorities of the National Incident Management System (NIMS) being standardized via DHS requirements.

However, movement in this direction must be based on the negotiated development of protocols and procedures among DOTs–state and local–public safety agencies, and the towing and recovery community to establish effective command, coordination, and response for effective management. Reaching agreements will require overcoming long-term institutional conventions that optimize individual agency objectives without regard to systems disruption. This integration dimension includes the ways in which data and information are shared and used by state DOTs (in real-time TMC activities) and connected agencies, organizations, and systems. This data and information exchange can be achieved through a range of means from verbal exchanges to automated electronic exchanges, and decision support systems that integrate available information to enhance operational efficiency and effectiveness.

- *Increased training* – Increased internal transportation agency as well as interagency training and interagency exercises to improve coordination and effectiveness covering such areas as overall response strategy, incident command, specific hazard related tactics, traffic control, etc.
- *Adoption of cost-effectiveness technology to improve efficiency, effectiveness, and safety* – Technology priorities and standard approaches must be identified and examined for their cost effectiveness. For state DOTs, many of the technologies that support improved emergency transportation operations are part of traffic operations-oriented ITS systems in various stages of cost-constrained deployment. In some cases, the effectiveness of technology depends significantly on the related analytics and utilization rather than simple deployment. The dual-use potential of ITS technology can be incorporated in the resource allocation process. Opportunities also exist for cost sharing among agencies.
- *Introductions of performance measurement in the field to provide the basis for continuous improvement* – Improvement in performance requires the establishment of clear objectives and related benchmarks, together with the measurement of task time and resource utilization for the various phases of emergency transportation operations. Agreement on what is to be measured across the traffic incident and emergency management community is essential. This can be considered with a formal process for review and identification and support for needed improvements.

NIMS emphasis	Obvious ETO Activities Based State DOT Best Practice
a. *Command and management structures*	
Incident command (ICS) procedures	On-going ICS training
Multi-agency coordination system	Memoranda of Understanding (MOUs with public safety agencies (PSAs)
Public information	Use of Overhead or Roadside information signs or radio broadcasts during incidents
b. *Preparedness*	
Planning	Incorporate NIMS in plan updates, as directed by state emergency management agency (EMA)
Training	Joint with PSAs, EMAs and other state and federal agencies (incorporating NIMS)
Exercises	Joint with PSAs, EMAs and other state and federal agencies (incorporating NIMS)
Personnel qualifications and certification	Varies
Equipment acquisition and certification	Varies
Mutual aid	Agreements executed – inter- and intrastate
c. *Resource management*	
	Resource typing/tracking (pre- and during incidents) will be introduced/managed by the state EMA)
d. *Communication and information management*	
IM communication	Communications management (contacts and information flow, interoperability, common architecture) as specified by state EMAs and/or in DOT's emergency operations plan
Information management	
e. Supporting technologies	
	Making DOT capacities known regarding communications, information management, surveillance and detection
f. *Ongoing management and maintenance*	
	Refinement and upgrading

EXHIBIT 7 Example Crosswalk Between National Incident Management Principals and Current State DOT Emergency Transportation Operations Approaches
Source: *AASHTO ETO Workshop, PB Consult*

- *Formalizing emergency transportation operations as a program with appropriate policies, authorization, organization, structure, and resources* – An effective approach will require "mainstreaming" real time systems operations as a more formal program within both transportation agencies and public safety agencies–in recognition of the special requirements of improved performance. An appropriate policy and program framework must be developed with organizational accountability and resources as the basis for continuous improvement. The impact of the security and safety thrust of the NIMS institutionalization will provide further impetus. In addition, a greater degree of formality is essential in the relationship between state DOTs and the public safety agencies to provide the basis for refining more effective roles and relationships towards interagency cooperation.
- *Aggressive Communication of weather-information* – The user-customer must be considered in the form of communication of weather-related changes in travel conditions to system users – for personal, business and commercial travel. Commercial vehicle operators, in

particular, who are concerned with just-in-time delivery need the opportunity to capitalize on the best available weather and weather related conditions data. This may involve making special arrangements with private suppliers of commercial vehicle information systems.

The combination of these suggested changes means transforming a set of *ad hoc* activities into a formal program and establishing binding interagency relationships, priorities, and procedures. Bringing together traffic incident management, weather disaster and emergency transportation operations, and other special emergency transportation preparations into a single management framework is at the core of improved transportation operations. Exhibit 8 suggests

PHASE	ACTIVITY
Preparations	Prepare response procedures & protocols: pre-event, during event, post event
	Develop decision support systems
	Equip infrastructure for operations and management
	Refine Policy/Performance Criteria
	Develop organization
	Develop external roles and relationships
	Joint training
	Legislation
Response	**Conditions Monitoring**
	measurement
	analytical routines
	tracking
	historical experience
	Threat Prediction
	decision support systems (type of impacts, incidence, severity, timing)
	Pre-Event
	mobilization
	pre-positioning equipment
	pre-treatment (ex: road chemicals)
	pre-mitigation (ex: avalanche control)_
	systems control regarding use of facilities, network
	evacuation
	advisories
	During Event
	continuing treatment (plowing)
	Traffic control
	incident monitoring (surveillance
	incident response and management
	FSP availability
	systems control regarding use of facilities, network
	advisory updates
Recovery (Post event)	Post-mortem re continuous improvement (feeds back to preparations

EXHIBIT 8 Phases of Transportation Incident and Emergency Operations

an organization of activities related to transportation systems operations broken down into the conventions of NIMS regarding road weather and emergency management.

Road Weather Management Within Transportation Operations

In the short run, it may be expected that "road weather management" as a discipline and set of activities will continue to develop within systems operations management. The current state of the practice in these areas is very uneven. It is not surprising the most aggressive applications of these technologies are located in states with the greatest weather disruption states–those with heaviest snow and ice incidents, states subject to hurricanes and others with special challenges such as fog and flooding.

Considerable thought has been given within the transportation community as to the key elements in a future comprehensive Road Weather Management System. (RWIs). As suggested by Exhibit 9, a range of research, new concepts, operational tests and field implementation (many of which are underway) need to be encouraged.

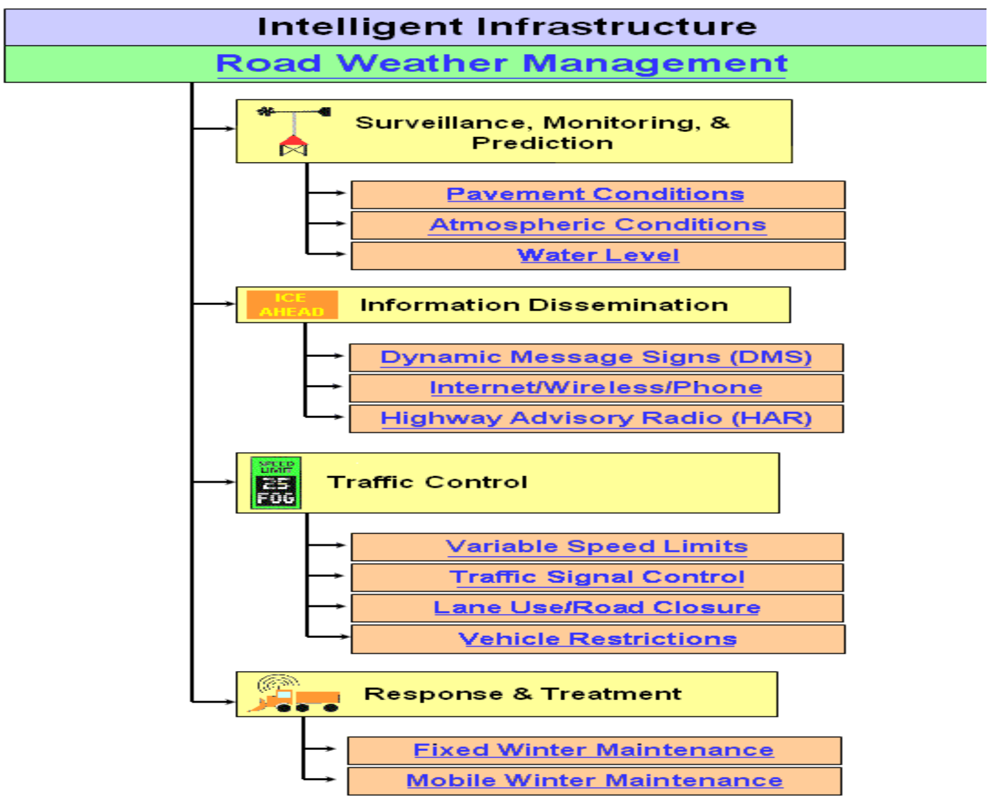


EXHIBIT 9 Road Weather Management Concept
Source: http://www.itsoverview.its.dot.gov/RWM.asp

Led by states with the greatest stakes and with federal government support, advances are being made regarding the integration of weather anticipation and highway operations. Five key areas of focus include:

- Surveillance, monitoring and prediction
- Decision support
- Treatment and control
- Special routines
- Information dissemination

Current Research and Development

In each of the above areas, there is considerable recent conceptual and technical development, focusing in particular on enhancing the observation capabilities and improving the decision support system. The FHWA and national weather entities have sponsored a series of research and development projects and supporting states in their implementation of advanced approaches. Some of the more important initiatives in improved information systems include:

- WIST – Weather Information for Surface Transportation is an interagency, inter-industry multiyear effort to identify the weather information needs of the surface transportations sector (all modes), including the key weather elements for each mode, information needed by operators, and the responsive research, technology transfer, data development and applications needs.
- COMET – the FHWA/National Weather Service Cooperative Program for Operational Meteorology, Education and Training (COMET) to foster collaboration between meteorological and transportation agencies for the creation of new predictive algorithms for use in road maintenance activities.
- FORTELL™ – an initiative by several State departments of transportation (Battelle 1998, funded partially by FHWA) that collects, forecasts, and distributes highly specific information on road and weather conditions pertinent to highway and trucking professionals, transit operators, commuters, long-distance travelers, and other road users.
- MDSS – since 1999 has been developing and field testing a Maintenance Decision Support System for snow and ice control operations integrating state-of-the art weather and road weather forecasting, data fusion, and optimization techniques with treatment and control logic for specific applications.
- CLARUS – initiative involves the integration of a nationwide network of environmental sensor stations that can support a range of weather prediction, analysis and notification activities.

Some of the key development issues that have grown out of the above experience–and the implied future directions and needs–are described below

Surveillance, Monitoring and Prediction This area focuses on capitalizing on the range of weather-related sensing resources – fixed, mobile and remote–assembling and analyzing data as part of a decision-support process to determine appropriate strategies. Many states have deployed meso-level networks of environmental sensor stations (ESS) and road weather information systems (RWIS), *in situ* sensors collecting a range of temperature, humidity, wind, visibility, and precipitation data as well as pavement temperature, moisture and other conditions. These systems also incorporate the macro-level national and regional information available from public and private sources, such as the National Weather Service.

Mobile sensing is a new concept utilized by a few states with vehicle-mounted devices able to profile road segments as an aid in mediating between macro weather and micro forecast needs. This includes not only special vehicles, but increasingly capitalizing on the sensors on standard production-line vehicles (rainfall, temperature, traction, etc.). Remote sensing is confined to the National Weather Service at present to support macro-scale conditions that can be fed into weather information networks.

Decision Support Increasingly, transportation managers are using the more timely and accurate route-specific environmental data becoming available to make treatment and control decisions to minimize temperature- and weather-related disruptions. Several projects have been undertaken by the FHWA in cooperation with states to develop decision support systems–some for maintenance, some for operations and others for specific purposes such as evacuation. A few states' traffic management centers have integrated simple decision support systems that integrate environmental data with traffic data to improve traffic control decisions. Some states have very specific weather-related sensing systems related to fog and flash-flood-prone locations. In all these areas strong federal leadership and inter-state cooperation is essential with local governments and authorities integrated into the institutional programs as well. The existing federal aid highway program provides a well-understood basis for this cooperation. What will require additional efforts are building institutionalized relationships with non-transportation entities with a weather and climate orientation such as the national weather related agencies and the private sector weather information supply services.

Various stakeholders in the DOT environment have differing decision support needs. This is focusing attention on data, analysis and communications of weather-related information. Key issues include:

- *Lead times* – Predictive time frames and uncertainty are important to planning operational strategies. This requires improved meteorological information and environmental prediction and archiving techniques. Advance lead time warnings are needed for appropriate time frames–not too great or little to be cost-effective (real long-range predictions are not necessarily useful for mobilization). The need appears to be for more accurate short-term forecasts appropriate to drivers (12 hours), freight (12-24 hours) and maintenance (24-48 hours).
- *Thresholds* – These address the need to provide data that are relevant to the particular weather-related threat context of the user. This may involve the expansion of definition of "weather" to include special highway-related needs (roadway and structure temperatures, ice accumulation and chemical presence). For example, states indicate that precipitation, temperature and winds appear to be the three most important, followed by visibility and flooding. Some states need information related to drifting snow–others do not. Desert states have a different threshold regarding what is a high temperature. Cold weather states need support in the identification of small-scale, weather-related hazards–for example, "invisible hazards" such as black ice.

- *Distribution* – There is a need for a means of correlating large quantities of information from static and mobile probes, including potential temperature, moisture, chemical concentration, friction, dew point precipitation, and visibility.
- *Resolution* – Probe-based road environment data are likely to be available (vehicle-infrastructure integration – VII). As intense or variable weather spreads, this issue may focus more on distribution of existing conventional point measurement technology than on more advanced technology. To capitalize on this micro-scale information, complementary advances are needed in modeling land surface phenomena.
- *Integration* – Improved interfacing with other non-weather information, hydrological data and types of analysis is required to support data re: weather-influenced phenomena such as flooding, local wind patterns and drifting snow, avalanches, and slides. This implies end-to-end models of traffic and weather, both "nowcast" and forecast, and the relationships to appropriate operational regimes. Other data integration requirements include:
  - Data filtering and fusion that is relevant to the specific operations-related treatment and/or control strategy available
  - More timely and accurate data (efficiency), dependent on integration of macro, meso, micro (i.e., how accurate does it need to be?)
- *Information transfer* – The value of the improved information will depend on more targeted real-time communication linkages with various decision support systems among interested parties (both producers and users of data) including traffic message channels (TMCs) and in-vehicle (telematics and VII). This may involve more direct user communications capitalizing on advanced communications as proposed in the VII program (see Resolution, above).

Institutional Integration Integration is beginning to occur at several levels. As indicated above, state consortia with common interests are working with FHWA and weather agencies to advance the technology of surveillance and decision support. Similar consortia are integrating weather information with dissemination networks. At the level of individual states, progress is being made regarding shared communications and protocols between PSAs, emergency management agencies and DOTs–especially in regions where the "price" of fragmentation is a visible public cost. In non-threatened environments, the stovepiping within state DOTs and between DOTs and other agencies involved in highway management is progressing–albeit slowly–with the help of major national efforts such as the National Incident Management Coalition. However, overcoming intuitional fragmentation remains a key challenge.

Treatment and Control Pre-treatment of pavement and bridges has becoming increasingly sophisticated, with improved road weather-related information–together with pre-positioning of equipment. The applications of sand and other anti-icing chemicals has become increasingly sophisticated regarding timing, mix and method of application. The control strategies utilized within the context of road weather management include the conventional range of operational tactics. The standardized concepts, functions and architecture and interfaces provided within ITS provide a clear sense of the relationships between information, relevant responses and the role of appropriate parties, as well as the features of specific control strategies, including route and variable speed restrictions, visibility and speed advisories via dynamic message signs, modified signal timing regimes, and accelerated incident management. Decision support systems in TMCs relate control strategy applications to specific road weather information configurations. This area remains an important focus for the overlap of research and applications

Special Routines Evacuation operations have received considerable attention over the last decade. While much attention within the transportation community has been given to traffic control (evacuation plans) and the complexities of reverse operations, the post-mortems of recent hurricanes have suggested that a much broader approach is important for the most significant events, including consideration of:

- Public communications and preparedness
- Handling people with special needs
- The role of other modes
- Evacuation-route support and related sheltering.

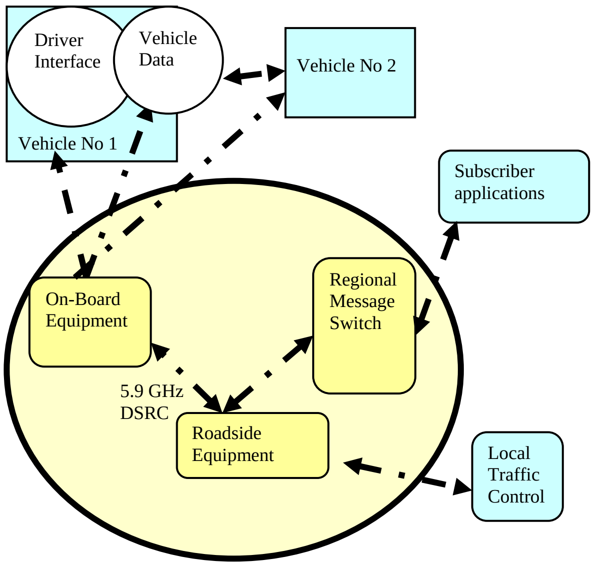
As in the case of agency operations in general, there is a very uneven level of preparation and capabilities among transportation agencies. Significant guidance is under development in this area–including for weather related emergencies at the "disaster" scale.

Information Dissemination Several states and consortia have web- and cellphone-based weather information systems, both specialized and via region and/or statewide 511 systems. Some of the more advanced systems integrate driver/user information with meso-level information on a road segment basis. Exhibit 10 describes the vehicle-infrastructure integration (VII) systems concept currently under development by a federal-state-industry consortium. This concept simultaneously provides vehicle-based probe data and in-vehicle driver information about traffic, weather, and other traffic management concerns. While the future of a formal single national government-industry program remains uncertain, such a program could have a major impact on the ability of state and local government to actively manage their highway systems.

The Long Run

The significant impacts of climate change are a long-run phenomenon and will be felt gradually over the next 50 to 100 years. During this period, it is not unreasonable to expect that state DOTs will gradually and continuously improve their capacities to provide the most efficient use of capacity, to minimize the impact of any disruptions to service (such as those related to weather) and to provide road-based emergency services.

As described above, there will be many factors that pace mainstreaming of operations over this period. One of these factors will be weather and the strength of the influence of weather will depend on how climate-induced weather impacts are experienced. The impact of climate-change induced weather changes will be experienced in two dimensions, as suggested in Exhibit 11.



VII functionalities

<u>Active safety applications</u> with real-time communications among vehicles and to roadside traffic control devices for intersection collision avoidance, violation warning, turn conflict warning, run-off-road departure warning,
<u>Vehicle diagnostics and maintenance applications</u> provide a means of communication between vehicle manufacturers and vehicle owners
<u>Mobility and road maintenance applications</u> via anonymous probe data and backhaul communications network, supporting road weather conditions data, construction zones, probe-based traffic management, pavement conditions, etc
<u>Driver/consumer convenience services</u> such h as traveler information, anti-theft services, vehicle diagnostics and auto manufacturer-customer relations

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EXHIBIT 10 Vehicle Infrastructure Integration Concept
Source*: VII Entity, PB Consult*

Mainstreaming Climate Change in DOT Operations Regime		
	Frequency: Institutionalization becomes C/E	
Intensity: Upgrade technology/procedures (Increase in threat levels)	Low frequency/High intensity • Prediction becomes important • Initiate new procedures • Introduce new technology	Moderate frequency/High intensity • Moves from operational to capital (risk-based in investment
	Low frequency/Moderate intensity • Consolidate into all-hazard for maximum efficiency using SOP	Moderate frequency/Moderate intensity • Consolidate into all-hazard for maximum efficiency using SOP • Threshold for extension of technology

EXHIBIT 11 Implications of Mainstreaming Climate Changes in DOT Operations Regimes

With changes in frequency and distribution, “minor” weather events will modify slightly the inventory of incidents that will be part of routine operations–along with other traffic disruptions–as part of day-to-day traffic and incident management. At some point in this evolution, an increase in “weather event” frequency becomes characteristic “climate” and the emergency response mode will no longer be efficient. For example, blizzards are routine in some Snow Belt states with highly standardized routines. An increased frequency in hurricanes in certain Gulf locations might lead to a similar routinization of hurricanes. As frequency of incidents related to weather increases, the prediction, detection, preparation and response “system” related to weather–both technology and protocols (such as sensing, analysis, pretreatment, etc.)–will become more routinized, rather than reactive. Eventually, high frequency events become a warrant for a design modification, rather than an operational condition–from a cost-effectiveness point of view. For example, regular flooding may suggest a design modification (improved drainage, elevated roadway) such that the weather event no longer requires and operational response.

With increases in intensity, more weather events will be considered general emergencies (as they will have impacts beyond transportation). Even current best practice operational strategy in vulnerable areas may require upgrading. The risks to life safety and property may require earlier warning and other actions such as evacuation. Prediction will become more important and, as the frequency of major storms increases, prediction will become more routinized. Integrated approaches will become more standardized and the transportation role (such as evacuation) will become more standardized as well, including capital investments to support operations such as detection, surveillance and message signs on evacuation routes. Hurricane evacuation routes and contra-flow infrastructure might become just as common as snow emergency routes in the upper Midwest. A similar spectrum might be expected for fog warning, flooding and other weather-related events. Certain road infrastructure might require design modification to handle new demands–related either to impact modification (such as drainage or snow storage) or to operations such as event-related surveillance. At some point these changes become non-marginal regarding operational implications until a dynamic conditions-responsive regime is no longer justified.

With changes in incidence, previously unaffected locations will gradually become subject to a new pattern of weather events. This may not require the development of new procedures or technology from an overall industry perspective, but it will involve the transfer of best practice to new locations.

These and other weather-related analysis and dissemination activities will become more important as the long-term dimensions and dynamics of climate-change-induced impacts are better understood. However, it must also be recognized that a transition will be taking place in the context of responding to incidents and emergencies that will affect the specific vectors for road weather information, treatment and control.

As the 21st century proceeds, it may be expected that pressure from demanding constituencies will focus state and local transportation agencies increasingly towards real-time provision of real-time, delay-free service. Regional and statewide DOT-sponsored Transportation Management Centers (TMCs) will become the cockpit for senior managers who will focus on monitoring and managing the performance of the transportation network, including weather-related disruptions and emergencies.

Climate change will become fully incorporated into systems operations and management as information, treatment and management technology advances. Each dimension of road weather information is likely to be impacted by climate change. Weather conditions information will have transitioned to a vehicle probe basis regarding both traffic and environmental conditions. Assuming the entire vehicle fleet is participating implies that such information will be continuously available everywhere, including both nowcasts and forecasts. Together with advanced analysis and archived historical data, probes will reduce the fixed-site monitoring data burden, and there will be a reduced need for micro- and meso-level fixed environmental sensor stations (ESSs). The high-resolution weather-related road conditions will be fully integrated into synoptic weather models and related operational models providing the basis for advanced treatment and controls. Management of the transportation operations procedures associated with major weather events will be finally calibrated to accurate lead-time forecasts of conditions at the micro level.

As prediction becomes more sophisticated, archival data, integration of macro and micro trends will allow regional agencies to better predict–and prepare for–long term trends. This is turn will support the development of more effective decision support technology and analyses and related research on needed treatment and control approaches. Road operational regimes for special strategies such as evacuation, detour, closings, or limitations will be based on pre-programmed routines, updated with real-time micro weather and traffic conditions information, and will utilize a combination of flexible facility controls (ramps, cross-overs) and in-vehicle advisories and controls.

At the same time, pavement, tire and treatment technologies are likely to advance to the point of minimizing the impacts of rain, minimal snow, ice, fog, etc. Weather-related control regimes will be expanded and automated, including integrated real-time road-vehicle regimes (stability, tracking, crash avoidance) that insure safety while maximizing level of service.

It may also be presumed that the institutional framework for prediction, surveillance, decision support and response will transition towards new weather-system–related scales–further reducing artificial state boundaries for effective information sharing and action. Weather information at this point will have transitioned from an unknown and fuzzy component of travel conditions and predictability to something highly reliable. This integration will extend out in time from minutes to days–and increasingly to the longer scales of climate change itself.

Appendix A

Climate Change-Related Weather Events and Operational Responses

CLIMATE CHANGE	EVENTS	OPERATIONS IMPACT (HAZARDS)	COMBINATIONS	REAL-TIME OPERATIONAL RESPONSE	OPERATIONS IMPROVEMENTS STRATEGY
TEMPERATURE	Higher/lower	• Extreme temperature indirect impacts	• Impacts frequency, intensity of weather events • Impacts frequency, intensity of weather events	• Changes in weight restrictions owing to rutting, buckling, bleeding • Change in length of construction season	• May require change in maintenance or design specifications
	Increase cycles	• Freeze/thaw indirect impacts			
WEATHER	Snowfall increase in depth, frequency	• Heavy coverage – with visibility and traction reduction – limits safe speeds, volumes, increases crash risks	• Combined with wind to impact drifting and visibility	• Pre-treat • Clear • Reduce speeds • Access controls • Closure • Lane controls • Tire controls • Advisories • Changes in signal timing	• Predict • Detect • Monitor • Treat • Control (various) • Disseminate information • Major coordination among traffic management , emergency responses and maintenance (and PSAs and EMAs)
		• Build up induces avalanches – presents life safety risk	• Combined with local topography and temperatures to		
	Sleet/hail incidence increase	• Produces black ice – with traction reduction -- limits safe speeds, capacity, increases crash risks	• Combined with temperature to impact icing		
	Humidity increase	• Produces fog – reduces visibility – reduces safe speeds, capacity, increases crash risks	• Combined with temperature to impact icing	• Reduce speeds • Closure	
	Rainfall amount and frequency	• Torrential rains- reduces traction, visibility – limits speeds, capacity, increases crash risks • Scour • Washout	• Combined with temperature to impact icing • Combines with contaminants to reduce traction	• Closures • Reduce speeds • Detours • evacuation • Closures • Manage drainage	

		• Riverine flooding – produces life safety risks (submersion) – limits speeds and capacity and routes			
		• Urban stormwater overflow – produces life safety risk (submersion) • Reduces speeds, capacity and routes			
		• Generates landslide – presents life safety risk, reduces capacity and routes.			
		• Drought produces wildfire conditions – with life safety risk, limits capacity, speed and route	• Combined with temperature to produce wildfire conditions		
	Hurricane frequency and strength	• Wind – produces life safety risk (overturning, downfalls, debris) and reduces routes			
		• Storm surge – produces life safety risks (submersion), power outages and reduces routes • Scour • Washout • Road damage • Appurtenance replacement			
	Tornado frequency and strength	• Winds -- produce life safety risk (overturning, airborne debris), power outages and reduce routes • Road damage • Appurtenance replacement			
	Lightning	• Bolts – present life safety risk, cause power outages, fires	• Combined with temperature and rainfall to produce wildfire conditions		

SEA LEVEL	General rise and Surges	• Flooding – produces life safety risks (submersion) and reduces route • Scour • Washout • Road damage • Appurtenance replacement	• Combine with rainfall and hurricane conditions to produce surges	• Closures • Reduce speeds • Detours • Evacuation • Closures	

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