Surface Transportation Safety and Operations:
The Impacts of Weather within the Context of Climate Change

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1.0 INTRODUCTION

Surface transportation is the dominant method of moving people and commerce in the United States. Services supporting surface transportation require usable infrastructure and effective systems. Primary highway operational goals—safety, mobility and productivity—are affected by environmental conditions. Weather acts through visibility impairments, precipitation, high winds, temperature extremes, and lightning to affect driver capabilities, vehicle maneuverability, pavement friction, and roadway infrastructure.

The Road Weather Management Program of the Federal Highway Administration (FHWA) has documented operational practices of traffic, maintenance, and emergency managers employed under various weather threats and the weather information needs of travelers. This paper examines weather impacts on roadways, operational practices of transportation managers and road users, and the weather parameters with the greatest effects on roadways. Finally, a discussion of how possible climate change may affect these parameters during the next century is presented.

2.0 OVERVIEW OF SURFACE TRANSPORTATION SAFETY AND OPERATIONS

Weather impacts roadway safety through exposure to environmental hazards and increased crash risk, either from impacts of a weather event or from the event's effect on the pavement. Each year 10 percent of passenger vehicle crashes occur in rain, snow, or sleet and approximately 13 percent of commercial vehicle (i.e., large truck) crashes happen in rain, snow, sleet, hail, or fog. Roughly 16 percent of commercial vehicle crashes occur on wet, snow-covered, slushy, or icy pavement each year. The combination of adverse weather and poor pavement conditions contributes to 18 percent of fatal crashes and 22 percent of injury crashes annually (National Center for Statistics and Analysis, 2001).

All U.S. residents are exposed to some form of weather-related hazards. Nearly 70 percent of the population and 74 percent of the nation's roads are located in snowy regions. Over 50 percent of U.S. residents have a five percent or greater chance of being affected by a hurricane in any given year. Most hurricane fatalities are related to inland flooding after landfall. Nearly 60 percent of deaths during Hurricane Floyd in 1999 were associated with drowning in vehicles from fresh water inundation and associated flooding.

Weather affects mobility by reducing traffic speed and volume, increasing travel time delay, and decreasing roadway capacity (i.e., maximum rate at which vehicles can travel). An Iowa State University study concluded that winter storms reduce average freeway speed by roughly 16 percent and traffic volume by 29 percent. Studies sponsored by the FHWA have found that weather accounts for roughly 12 percent of travel time delay in two metropolitan areas. A nationwide study conducted for FHWA estimated that 23 percent of delay and 11 percent of capacity reductions resulted from fog, snow and ice in 1999. These weather events were the most prevalent causes of non-recurrent traffic congestion.

Weather events impact transportation system productivity by increasing operating and maintenance costs and by disrupting access to roadway networks. Nearly 39 percent of road operating costs can be attributed to winter maintenance annually. Each year, state and local agencies spend over 2.3 billion dollars on snow and ice control operations and an estimated five billion dollars to repair roadway infrastructure damaged by snow and ice.

3.0 REVIEW OF OPERATIONAL PRACTICES

Transportation managers utilize three types of operational practices to mitigate environmental impacts on roadways: advisory, control, and treatment strategies. These mitigation strategies are employed in response to various weather threats including fog, rain, snow, ice, high winds, flooding, tornadoes, hurricanes, and avalanches. Advisory strategies provide information on prevailing and predicted conditions to both managers and motorists to influence operational decisions. Control strategies alter the state of roadway devices (e.g., traffic signals, ramp gates) to regulate roadway capacity and permit or restrict traffic flow. Treatment strategies supply resources to roads (e.g., spreading sand or salt) to minimize or eliminate weather impacts.

Transportation managers use environmental and traffic data to make decisions about system operation and resource deployment. Weather threat information is typically gathered through surveillance systems that detect and transmit data from roadways to central systems accessed by managers. Environmental sensor stations (ESS) are deployed along roads across the country to observe atmospheric, pavement, subsurface, water level, and slope stability conditions. Environmental data may be integrated into road weather information systems (RWIS), advanced traffic management systems (ATMS), emergency management systems (EMS), and advanced traveler information systems (ATIS) as depicted in Figure 3.1. Vehicle detectors and closed circuit television (CCTV) cameras are components of ATMS used to monitor traffic conditions. By integrating accurate, timely road weather data into decision-making processes, transportation managers can effectively counter

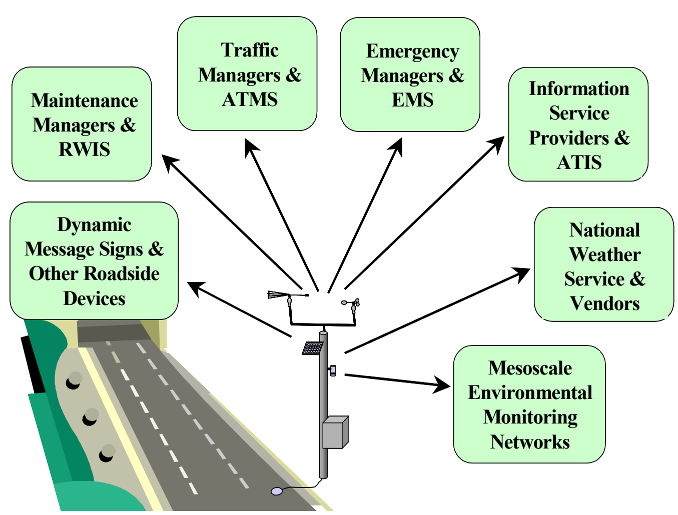

Figure 3.1 ESS operational applications, showing the many users of ESS data

weather-related problems and disseminate relevant, credible information that allows travelers to avoid unsafe conditions or cope with weather effects.

3.1 Operational Practices of Maintenance Managers

Maintenance managers obtain surveillance and predictive information to assess the nature and magnitude of an environmental threat. These information resources help managers make decisions about staffing levels, road treatment strategies, the timing of maintenance activities (e.g., crack sealing operations in summer months), and resource management (i.e., personnel, equipment, and materials).

Winter road maintenance involves removing snow and ice through mobile techniques or fixed systems. Snow and ice treatment strategies include plowing snow, spreading abrasives (e.g., sand) to improve vehicle traction, and dispensing anti-icing/deicing chemicals (e.g., salt, magnesium chloride, potassium acetate) to lower the pavement freezing point. In regions with heavy snowfall, maintenance managers may erect snow fences adjacent to roads to reduce blowing and drifting snow.

Another mitigation strategy involves use of slope sensors and avalanche forecasts to minimize landslide and avalanche risks. When a slope becomes unstable due to snow accumulation or soil saturation, roads in the slide path may be closed to allow the controlled release of an avalanche or landslide. After snow, mud and debris are cleared and damaged infrastructure is repaired the affected route can be reopened to traffic.

In mountainous areas, super-cooled fog can persist in valleys for weeks. To improve roadway visibility and reduce crash risk, managers can employ a fog dispersal treatment strategy. Small amounts of liquid carbon dioxide are sprayed behind maintenance vehicles to encourage precipitation of water droplets in the fog. This strategy includes the application of anti-icing chemicals as fog is dispersed to prevent the precipitate from freezing on road surfaces.

Maintenance vehicle management practices involve treatment planning, real-time operations monitoring, and post-storm analysis. Managers may consult decision support systems to plan the most efficient treatment routes, select treatment chemicals, and dispatch crews. Truck-mounted sensor systems facilitate surveillance of road conditions and tracking of vehicle status (e.g., truck speed, plow position, material application rate) with automated vehicle location, global positioning system, and geographical information system technologies.

Table 3.1 lists several advisory, control and treatment strategies exploited by maintenance managers and the resulting effects on roadway safety and operations. These strategies improve safety by reducing crash frequency and minimizing risks to field personnel and motorists. Increased visibility distance and roadway capacity enhance mobility. Productivity is improved by preventing vehicles from interfering with winter road maintenance and by minimizing road maintenance costs.

Table 3.1 Operational Practices of Maintenance Managers

	Mitigation Strategies	Safety & Operational Effects
Advisory	Surveillance/Prediction • atmosphere (temperature, precipitation, visibility, wind) • pavement temperature/condition • subsurface temperature/condition • water level & flooding • slope stability (i.e., avalanche/landslide onset)	• assess nature/magnitude of threat (e.g., impaired paving, lane obstruction, loss of vehicle stability) • determine threatened areas/routes • select appropriate treatment strategy • mobilize personnel (e.g., prepare/load vehicles) • determine risks to field personnel (e.g., hypothermia) • determine risks to roadway infrastructure (e.g., pavement buckling, lane submersion)
Treatment	Winter Road Maintenance • conventional snow/ice control (e.g., plow snow, spread sand) • apply anti-icing/deicing chemicals • erect snow fence	• improve visibility (safety) • reduce crash risk (safety) • improve vehicle traction (mobility) • increase roadway capacity (mobility) • minimize treatment costs (productivity)
Control & Treatment	Avalanche/Landslide Control • road closure • release avalanche/landslide • clear roadway & repair damaged infrastructure	• minimize risks to public (safety) • minimize risks to field personnel (safety) • reduce length of road closure (mobility)
Treatment	Fog Dispersal • spray carbon dioxide into super-cooled fog • apply anti-icing/deicing chemicals	• reduce crash risk (safety) • increase visibility distance (mobility)
Advisory	Maintenance Vehicle Management • route planning • automated vehicle location • vehicle system status (e.g., plow blade up) • treatment monitoring (e.g., application rate) • post-storm analysis (e.g., plow passes per route)	• minimize treatment costs (productivity) • minimize maintenance costs (productivity)

3.2 Operational Practices of Emergency Managers

Emergency managers obtain current and predicted weather information through RWIS, water level monitoring systems, the federal government (e.g. the National Hurricane Center), private companies, the media, and various decision support systems. Decision support systems may present weather data integrated with population data, topographic data, and road and bridge locations, as well as traffic flow data. In response to flooding, tornadoes, hurricanes, wild fires or hazardous material incidents, emergency managers can evacuate vulnerable residents, close threatened roadways and bridges, operate outflow devices to lower water levels, and disseminating information to the public. Many emergency management practices require coordination with traffic and maintenance managers.

Evacuation management begins with an advisory strategy. Emergency managers gather weather observations and forecasts to identify hazards, their associated threatened areas, and select a response or mitigation strategy. Managers may use several control strategies to manage traffic on designated evacuation routes. These strategies include opening shoulder lanes to traffic, contraflow operations to reverse traffic flow in selected freeway lanes, and modified traffic signal timing on arterial routes.

Emergency managers deploy environmental sensors (e.g., rain gauges) to monitor precipitation and water level conditions. Surveillance data are used to identify areas that may be significantly impacted by heavy rainfall. To prevent or alleviate flooding it may be necessary to activate outflow devices to control the release of water.

Some emergency management practices and effects on roadway safety and operations are shown in Table 3.2. Control strategies increase roadway mobility by reducing travel time delay or by maintaining adequate roadway capacity to ensure public safety. Emergency managers must disseminate evacuation orders, road closure and flood information to minimize exposure to hazards.

Table 3.2 Operational Practices of Emergency Managers

Mitigation Strategies		Safety & Operational Effects
Advisory	Surveillance/Prediction • atmosphere (storm track, precipitation, wind) • water level & flooding • traffic volume (e.g., route-specific, state-to-state) • travel time	• assess nature/magnitude of threat (e.g., hurricane storm surge, hail size, wind speed) • determine threatened areas/routes • select appropriate response strategy • mobilize personnel (e.g., preposition equipment) • determine risks to roadway infrastructure (e.g., lane submersion, loss of communications) • eliminate field measurements (productivity)
Control	Evacuation Management • determine evacuation type/timing (e.g., voluntary, mandatory, phased) • open shoulder lanes • contraflow (e.g., reverse freeway lanes) • modify traffic signal timing	• minimize risks to public (safety) • minimize risks to field personnel (safety) • increase roadway capacity (mobility) • minimize travel time delay (mobility)
Control	Flood Control • operate outflow devices to induce drainage	• minimize risks to public (safety) • minimize risks to field personnel (safety)
Advisory	Disseminate Road Weather Information (e.g., storm track, threatened routes, access restrictions)	• minimize risks to public (safety) • minimize risks to field personnel (safety)

3.3 Operational Practices of Traffic Managers

Roadway conditions are monitored from traffic management centers (TMCs). Most traffic managers access weather forecasts from the commercial sector including the media. Customized weather forecasts are also utilized in many TMCs and weather data are integrated with control software in some TMCs. Based upon weather surveillance or prediction data, managers execute control strategies to manage traffic flow and advisory strategies to disseminate road weather information.

Traffic signal timing plans may be altered in adverse weather conditions to accommodate slower travel speeds on "wet", "slushy", "snowy", or "icy" roads. Traffic managers may modify incident detection software algorithms for "sunny", "rainy", "snowy", "dry pavement" or "wet pavement" conditions to identify traffic flow disruptions on freeways.

Another control strategy utilized by traffic managers is speed management. Speed limits are changed based upon the safe travel speed for prevailing visibility, pavement, and traffic conditions. Managers notify drivers of reduced speed limits via dynamic message signs (DMS) or variable speed limit (VSL) signs.

When travel conditions are unsafe due to low visibility conditions, lane obstructions, excessive snow accumulation or flooding, managers may restrict access to entire road segments, specified lanes, bridges, all vehicles, vehicles without required equipment (e.g., tire chains), or designated vehicle types (e.g., tractor-trailers). Dynamic message signs and lane use signs are typically used to inform motorists of travel restrictions.

When visibility is reduced by fog or wind-blown dust, managers may guide vehicles by illuminating pavement lights embedded in road surfaces or bridge decks to delineate travel lanes. Traffic and emergency managers also cooperate to guide vehicle platoons in low visibility conditions. Patrol vehicles with flashing lights may be used to group traffic into platoons. Patrols, at the front and the rear of a platoon, lead traffic through affected areas at a safe pace.

Traffic management practices and associated effects are shown in Table 3.3. Advisory and control strategies improve safety by reducing traffic speeds and crash risk, and enhance mobility by delineating travel lanes and minimizing delay.

Table 3.3 Operational Practices of Traffic Managers

Mitigation Strategies		Safety & Operational Effects
Advisory	Surveillance/Prediction • atmosphere (temperature, precipitation, visibility, wind) • pavement temperature/condition • subsurface temperature/condition • water level & flooding • traffic volume • traffic speed	• assess nature/magnitude of threat (e.g., low visibility, loss of vehicle traction) • determine threatened areas/routes
Control	Weather-Related Signal Timing (i.e., modify green time, modify cycle length)	• reduce speed (safety) • reduce crash risk (safety) • prevent traffic congestion (mobility)
Control	Weather-Related Incident Detection (i.e., modify detection algorithms)	• minimize incident response time (safety) • reduce risk of secondary incidents (safety) • minimize delay (mobility)
Control	Speed Management • determine safe speed • reduce speed limit	• reduce speed & speed variance (safety) • reduce crash risk (safety)

	Mitigation Strategies	Safety & Operational Effects
Control	Access Restriction (on threatened routes) • road/bridge/ramp closure • tire controls (e.g., tire chains, snow tires) • lane use controls • designated vehicle types (e.g., trucks)	• reduce crash risk (safety) • minimize risks to public (safety) • minimize risks to field personnel (safety) • minimize delay due to treatment (mobility) • minimize treatment costs (productivity)
Control	Vehicle Guidance (in low visibility conditions) • illuminate pavement lights • lead convoys at safe speed with patrol vehicles	• delineate travel lanes (mobility) • reduce crash risk (safety)
Advisory	Disseminate Road Weather Information (e.g., access restrictions, safe speed) • roadway warning systems • interactive telephone systems • web sites	• reduce speed & speed variance (safety) • reduce crash risk (safety) • minimize risks to public (safety) • promote uniform traffic flow (mobility)

3.4 Operational Practices of Travelers or Road Users

Transportation managers disseminate road weather information to all road users to influence their travel decisions. Different types of travelers, or road users, have varying information needs. In the event of a road closure recreational travelers may need alternate route information, while commuters familiar with their route may not. Passenger vehicle drivers are interested in road surface conditions and commercial vehicle operators need information about road restrictions due to subsurface freeze/thaw conditions. Road weather information allows travelers to make decisions about travel mode, departure time, route selection, vehicle type and equipment, and driving behavior.

Road weather warnings and regulations may be furnished via roadway warning systems, telephone systems, web sites, and other broadcast media. Roadway warning systems—which are typically controlled by traffic managers—utilize highway advisory radio transmitters, DMS, VSL signs, and flashing beacons atop static signs to alert motorists to hazards. Interactive telephone systems allow motorists to access road weather information before a trip and while en-route. Many state departments of transportation (DOTs) provide general road condition data through toll-free telephone numbers and via 511, the national traveler information telephone number, which was allocated by the Federal Communications Commission in 2001. Travelers may also access tailored road weather information provided by private vendors. For example, drivers in Minnesota, Montana, North Dakota, and South Dakota can dial #7233 (or #SAFE™) to obtain route-specific road condition reports and six-hour weather forecasts extending 60 miles (or one hour) in their direction of travel. Many state DOTs also provide textual and graphical road weather information on Internet web sites. Mitigation strategies employed by travelers to improve safety are listed in Table 3.4.

Table 3.4 Operational Practices of Travelers or Road Users

	Mitigation Strategies	Safety & Operational Effects
Advisory	Access Road Weather Information • warnings/regulations via roadway devices • tailored road weather data via telephone • road weather data posted on web site	• determine mode, route & departure time • select vehicle type & equipment
Control	Make Travel Decisions • defer trip • prepare vehicle • drive slower • increase following distance	• reduce speed (safety) • reduce crash risk (safety)

4.0 WEATHER PARAMETERS AFFECTING SAFETY AND OPERATIONS

Weather is complex and dynamic. It affects operations and planning for all surface transportation modes. While great strides have been made in improving short and long range forecasting, there is still a significant gap between the state-of-the-art and what is needed to provide a full suite of accurate, high-resolution meteorological guidance to roadway operators and users.

Looking into the future, transportation professionals will be able to utilize new technologies for decision support. However, they must also be able to adapt to potential changes in global climate. This section will rank and discuss those weather parameters that most affect the safety and operations of roadways and how climate change may affect the parameters.

It is apparent in the previous section that there are many weather parameters that affect highway safety and operations. A previous effort to describe all the parameters was completed on behalf of the Office of the Federal Coordinator for Meteorology. This was done as part of a broader effort to capture the weather information needs for the entire surface transportation community. Since it is not feasible to examine all these parameters in the context of climate change, only those weather parameters that have significant affects on maintenance management, emergency management, traffic management, and road users are identified and prioritized below. Weather parameter rankings are based on experience and observations of each discipline, rather than extensive analysis. Ranking criteria include area of influence (i.e., portion of the country that is affected by the weather condition), frequency of occurrence (i.e., seasonal or year-round effects), impact on roadway operations, and ease of mitigation. Table 4.1 provides a listing of weather parameter rankings for each operational area. The sections that follow briefly describe how each parameter affects roadway operations and safety, and the potential impacts from climate change.

Table 4.1 Weather Parameters that Most Affect Roadway Safety and Operations

Rank	Maintenance Management	Emergency Management	Traffic Management	Road User/ Traveler
1	Ice	Severe Storms	Snow/Ice	Snow/Ice
2	Snow	Tropical Cyclones	Severe Storms	Low Visibility
3	Road Temperature	Winter Storms	Tropical Cyclones	Severe Storms
4	Severe Storms	Wind (Dispersion Info)	Low Visibility	Wind (Vehicle Stability)

4.1 Potential Climate Change

This paper is not a vehicle to discuss the validity, magnitude nor duration of projected climate change. Rather, the discussion will take one viewpoint and apply these hypotheses to each weather parameter listed in Table 4.1. The Environmental Protection Agency (EPA), citing studies performed by the National Academy of Sciences, has indicated that a buildup of greenhouse gases in the Earth's atmosphere has hastened a global trend of rising surface temperatures. Using the United Kingdom's Hadley Centre climate model, the EPA has written reports on the impacts of potential climate change during the twenty-first century for each state. Table 4.2 contains a compilation of potential climate change projections with respect to both air temperature and precipitation.

The seasonal projected temperature changes for each state by the year 2100 are listed in the temperature columns. From these data, the following projections can be made:

- Average U.S. air temperatures are projected to increase by 3.5 degrees (Fahrenheit) in the spring, by 3.7 degrees in the summer, and by 4.0 degrees in both the fall and winter.

- The greatest temperature rise is forecast to occur over Alaska during the winter with an average increase of 10 degrees.

- During the summer season, the area with the smallest projected temperature rise extends from the Midwest to the southern mid Atlantic coast. The areas with the largest projected rise are New England and the western states.

- During the winter season, the area with the smallest projected temperature increase extends over the Deep South and Gulf coast states. The area with the largest projected rise (outside of Alaska) is along and west of the continental divide.

Precipitation models also forecast a general increase during this century across the nation. However, unlike temperature, there are a few locations that are actually projected to have a net decrease in precipitation amounts. These areas are centered over the intermountain region and the desert southwest during the summer season. Additional precipitation related estimates include:

- The average amount of precipitation across the country is projected to rise by 10.7 percent in spring, by 14.1 percent in summer, by 16.2 percent during fall and by 19.0 percent during winter.

- Precipitation projections for Hawaii could not be determined due to uncertainties associated with Pacific Ocean currents and phenomena such as El Nino.

- Florida is the only state to have a projection of no change in precipitation amount in any season.

- Winter precipitation amounts are forecast to increase (by over 30 percent) along the eastern seaboard due to the potential for more frequent nor'easters.

Table 4.2 Composite of Projected Climate Change by the Year 2100[1]
Source: U.S. Environmental Protection Agency (2002), Global Warming – State Impacts

State	Temperature				Precipitation				State	Temperature				Precipitation			
	Sp	Su	Fa	W	Sp	Su	F	W		Sp	Su	F	W	Sp	Su	F	W
AL	3	2	4	2	10	15	15	0	MT	4	4	5	5	10	10	10	30
AK	5	5	5	10	10	10	5	5	NE	3	3	4	4	10	10	10	15
AZ	4	5	4	5	20	-10	30	60	NV	4	6	4	6	15	-10	30	40
AR	3	2	3	2	15	25	15	0	NH	4	5	5	5	0	10	10	40
CA	3	5	3	5	30	0	30	40	NJ	4	5	5	4	10	20	20	30
CO	4	6	4	6	10	0	10	40	NM	3	5	4	5	15	-5	5	30
CT	4	4	4	4	10	20	20	40	NY	4	5	5	4	10	20	20	30
DE	3	4	4	4	15	30	15	40	NC	3	2	3	2	15	20	20	15
FL	4	4	4	3	0	0	0	0	ND	4	3	4	4	5	10	15	25
GA	3	2	4	3	10	30	30	10	OH	3	3	4	3	15	25	20	15
HI	3	3	4	3					OK	2	3	3	4	20	20	5	0
ID	4	5	4	5	10	0	10	20	OR	4	5	4	5	5	-5	15	15
IL	3	2	4	3	10	50	30	10	PA	5	3	3	5	10	20	50	20
IN	3	2	4	3	10	30	20	10	RI	4	5	5	4	10	10	15	25
IA	3	2	4	4	10	20	15	10	SC	4	2	4	2	15	20	20	10
KS	2	3	4	4	15	15	15	0	SD	3	3	4	4	10	10	10	20
KY	3	2	4	3	20	30	20	0	TN	3	2	4	3	20	30	20	5
LA	3	3	4	2	0	10	10	0	TX	3	4	4	4	10	10	10	-15
ME	3	5	3	5	0	10	10	30	UT	4	6	4	6	10	-10	30	40
MD	3	4	4	4	10	20	10	30	VT	4	5	5	5	0	10	10	30
MA	4	5	5	4	10	10	15	40	VA	3	3	4	3	20	20	20	20
MI	4	4	4	4	10	20	10	10	WA	4	5	4	5	0	0	0	10
MN	4	3	4	4	0	15	15	15	WV	3	3	4	3	20	25	20	20
MS	3	2	4	2	10	15	15	0	WI	4	3	4	4	0	20	20	20
MO	3	2	3	3	15	40	15	0	WY	4	5	4	6	10	-5	10	30

[1] Temperature values under are in whole degrees Fahrenheit. Precipitation values represent percentage change from the present climatological norm. Decreases in precipitation are shown in lightly shaded cells. Unknown values are shown in darkly shaded cells.

4.2 Maintenance Management

The weather parameters with the greatest affects on maintenance management are ice, snow, road temperature, and severe storms. The following sections describe how these parameters affect road maintenance, and how the potential climate change scenario presented in Section 4.1 could impact management practices in the future.

4.2.1 Ice Impacts on Maintenance Management

The occurrence of ice on the pavement is one of the most hazardous conditions for all road managers and users. Ice can form directly on roadway surfaces (e.g., black ice or frost), or can fall as precipitation in the form of freezing rain, freezing drizzle or sleet. While the former can occur anywhere outside of the more tropical climates (e.g., south Florida), the map in Figure 4.1 shows that freezing precipitation occurs with the highest frequency over the central and upper plains, extending east to New England and south over the mid-Atlantic region in the lee of the Appalachian Mountains. High frequencies can also be seen over portions of the Northwest.

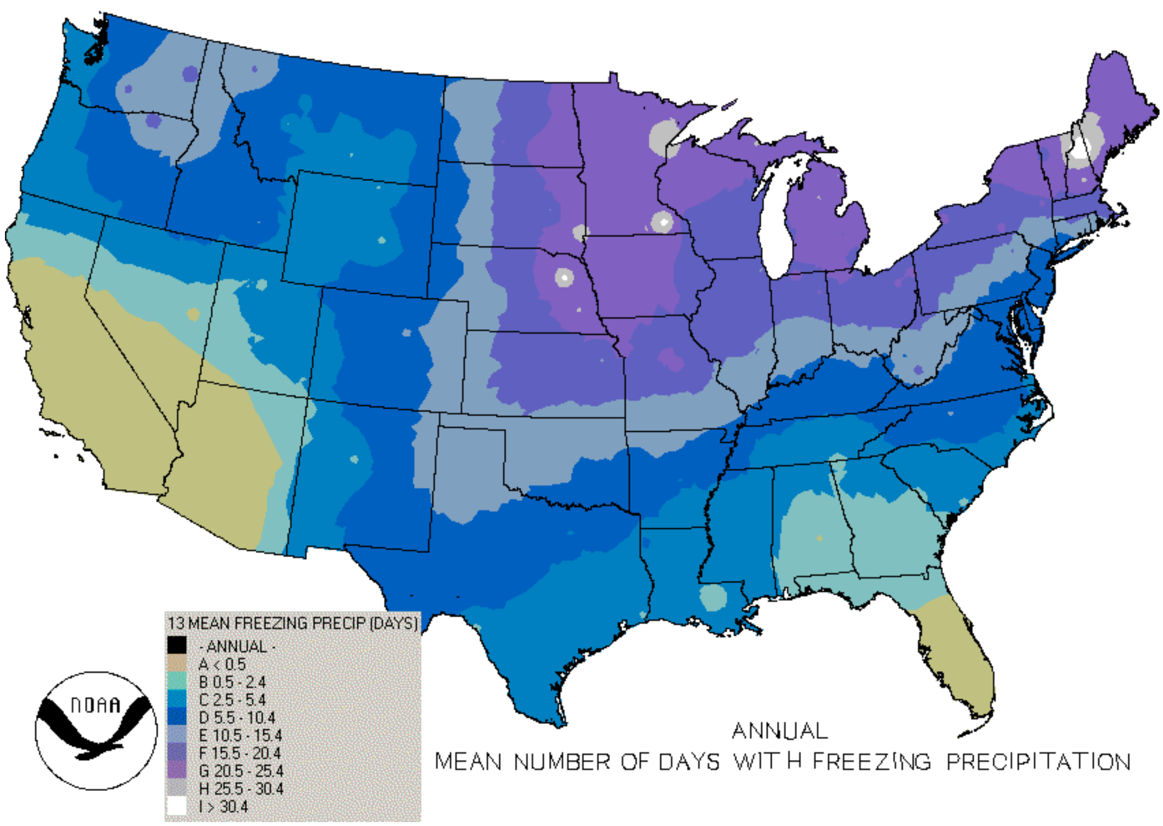

Figure 4.1 Annual Mean Number of Days with Freezing Precipitation Observed
Source: National Climatic Data Center, 2000

With respect to maintenance management, there are many hazards to roadway safety and operations associated with surface icing. Icing causes a loss of pavement friction, which can reduce maintenance vehicle stability and maneuverability, as well as increased winter road maintenance costs. There is also the potential for lane obstruction and infrastructure damage due to ice accretion on pavement, tree limbs, power lines, and communication equipment. Elevated bridges, ramps, and roads out of direct sunlight are at the greatest risk for icy surface conditions.

Climate change projections indicate that in general both winter temperatures and precipitation could increase over the next century. However, that does not necessarily translate into less ice. Moderation in atmospheric temperature could allow precipitation, which would otherwise fall as snow, to become freezing rain or sleet. This is a consequence of relatively warm moisture falling through colder air masses close to the surface. This could increase the frequency, duration, and amount of ice that occurs particularly from the mid-Atlantic piedmont north to New England and west into the midwestern states. This would require that road maintenance agencies in these regions budget for increased maintenance activities and utilize more effective techniques, such as proactive treatment, to handle potentially treacherous conditions.

4.2.2 Snow Impacts on Maintenance Management

Snow occurs with greater frequency than ice and can cover a larger area in an individual storm. In general, the snow threat region only covers about two-thirds of the nation. Figure 4.2 shows the mean number of days per year that snowfall accumulates to one inch or more. This graphic clearly delineates those regions of the continental United States that are affected by snowy conditions. The frequency of snowfall is very low over the entire southern tier of states, portions of the southwest, and much of the west coast. Snow reduces maintenance vehicle maneuverability, increases winter road treatment costs, and increases the potential for avalanches.

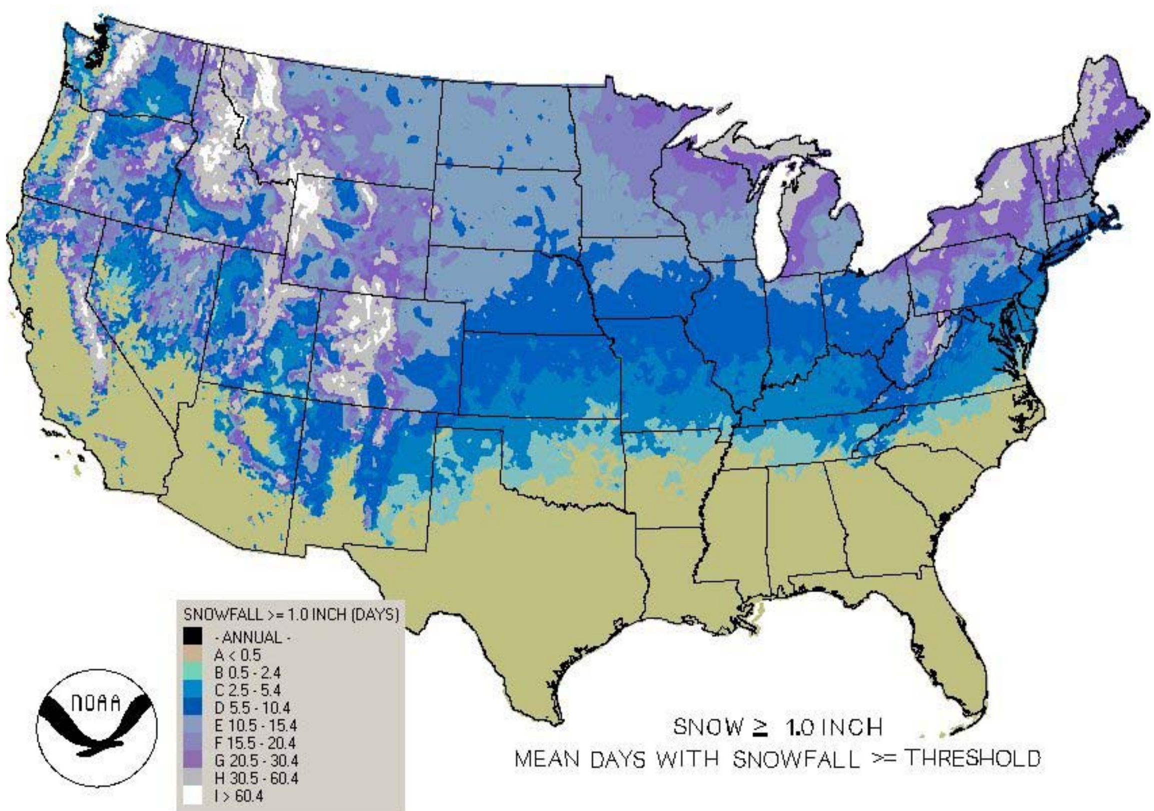

Figure 4.2 Mean Number of Days with Snowfall of One Inch or Greater
Source: National Climatic Data Center, 2000

Long-term climate projections indicate that mean winter temperatures will increase more than in any other season. On average, this could reduce the areal extent and duration of snow impacting the country's roads. It is possible that the southern fringes of snowy regions shown in Figure 4.2 will retreat northward. Warmer ocean temperatures could also provide for more mixed precipitation along the urban corridor from Washington, D.C. into New England. However, the frequency and intensity of nor'easters may increase and affect interior portions of the mid-Atlantic region into interior New England providing the potential for more disruptions from snow. Under this scenario, maintenance managers may have to increase budgets for snow removal in these areas. However, regions ranging from the Carolinas west across the Tennessee Valley into the central plains may see a reduction in winter maintenance costs.

4.2.3 Road Temperature Impacts on Maintenance Management

Road surface temperatures play a significant role in determining the effectiveness of winter treatment strategies and resulting pavement conditions. Dark pavement can efficiently absorb daytime solar radiation, potentially storing heat overnight or for the beginning of a precipitation event. However, if pavement temperature falls below freezing in the presence of precipitation or surface moisture, ice can form and pavement friction will be reduced affecting maintenance vehicle operations. In addition, pavement temperature can affect the bonding of ice to road surfaces, which can make treatment more difficult and more costly.

An estimation of rising cold season temperatures would act to reduce the total number of days with freezing temperatures, particularly along the coastal plain along the Gulf and Southeast coasts. However, the temperature rise could create more frequent freeze/thaw cycles in areas that currently experience freezing over longer durations. This could cause infrastructure damage in the form of buckling, heaving or water main breaks, as well as an increase in the number of frost or black ice events.

4.2.4 Severe Storm Impacts on Maintenance Management

Severe convective storms, or thunderstorms, can occur at any time of the year, over the majority of the country, with the highest likelihood of occurrence in the Southeast and the Great Plains, as shown in Figure 4.3. They typically have a short duration, are somewhat limited in areal coverage, and usually occur during warmer months. Though rare, thunderstorms can occur in winter. Thunderstorms can produce a plethora of dangerous conditions ranging from torrential rains, low visibility, lightning, damaging winds, hail, and on rare occasions a tornado or even blinding snow. These conditions can cause infrastructure damage (e.g., lane submersion, debris on roads) and reduce the productivity of road maintenance crews (e.g., impaired paving).

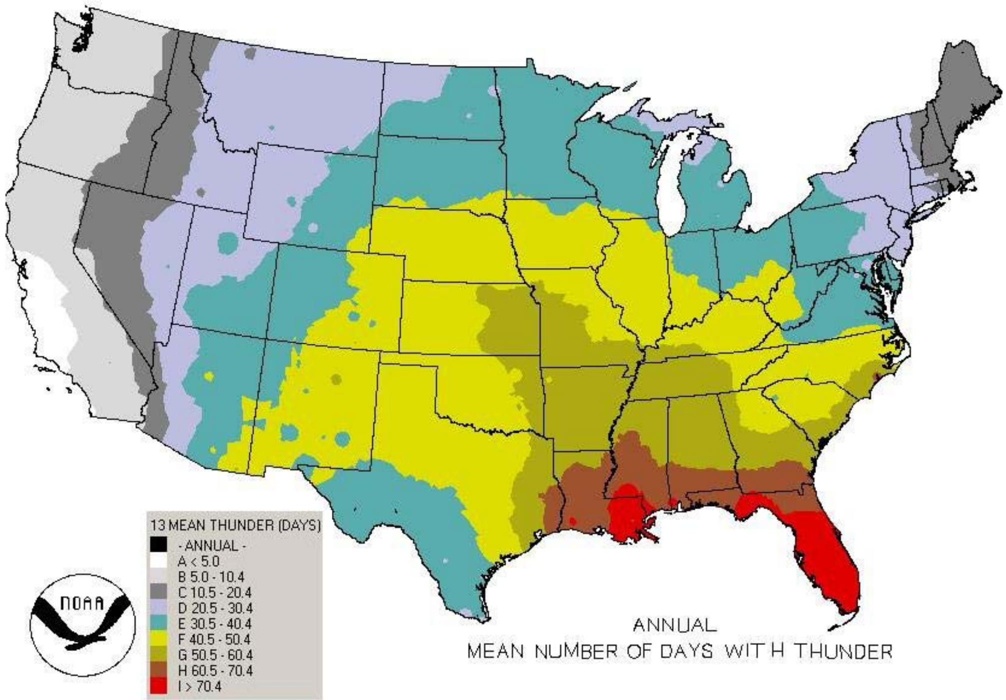

Figure 4.3 Annual Mean Number of Days with Thunder Observed
Source: National Climatic Data Center, 2000

The "thunderstorm season" typically extends from April through the summer and tapers off in November. A trend of overall warming could extend this season at both ends. Additionally, there could be an increase in storm intensity due to warmer daytime temperatures and higher atmospheric moisture content. This trend could lead to more disruptions of road maintenance activities and necessitate more frequent repair of damaged infrastructure decreasing productivity.

4.3 Emergency Management

Severe storms, tropical cyclones, winter storms and high winds are the weather parameters with the greatest effects on emergency management. The following sections detail how emergency management activities are impacted by these phenomena.

4.3.1 Severe Storms Impacts on Emergency Management

Severe storms can produce a number of adverse conditions year round. Torrential rains can induce roadway flooding. High winds and tornadoes can produce swaths of devastation toppling trees and bringing down power lines. Large hail can damage property and lightning can affect power grids and start fires. Severe storms have the highest rank for emergency management due to their frequency of occurrence and high risks of roadway infrastructure damage.

Severe convective storms occur primarily during spring and fall seasons in the months of April and May and the months of September and October when air masses are under the greatest transition. Projected warming could extend these seasons earlier in the spring and later in the fall (e.g., March through May and September through November). The frequency and intensity of these storms may also increase due to warmer temperatures and increased atmospheric moisture.

This trend could shift the focus of some emergency managers toward activities aimed at handling warm season storms and resulting flooding.

4.3.2 Tropical Cyclone Impacts on Emergency Management

As coastal populations grow, the likelihood that a land falling hurricane will have devastating effects increases. Hurricanes produce coastal storm surge and high winds that can undermine or submerge roads and damage communications infrastructure. Tornadoes embedded within a hurricane can also produce areas of total devastation. While weak tropical systems can produce significant floods, major structural damage is usually limited to relatively rare, major hurricanes (i.e., Category 3 or higher).

Hurricanes can affect a large area and have significant impacts on emergency management operations, both before and after a landfall. Hurricane track, precipitation, and wind speed forecasts factor into management decisions to issue evacuation orders and manage traffic on evacuation routes. The map in Figure 4.4 shows the chance (based on climatology) that a tropical storm or hurricane will affect some portion of the eastern U.S. during the hurricane season (June through November). Based on these statistics, both Miami and Cape Hatteras are at the highest risk for being affected by a tropical cyclone, at 48 percent. South Florida is at the highest risk of being struck by a major hurricane, at four percent annually.

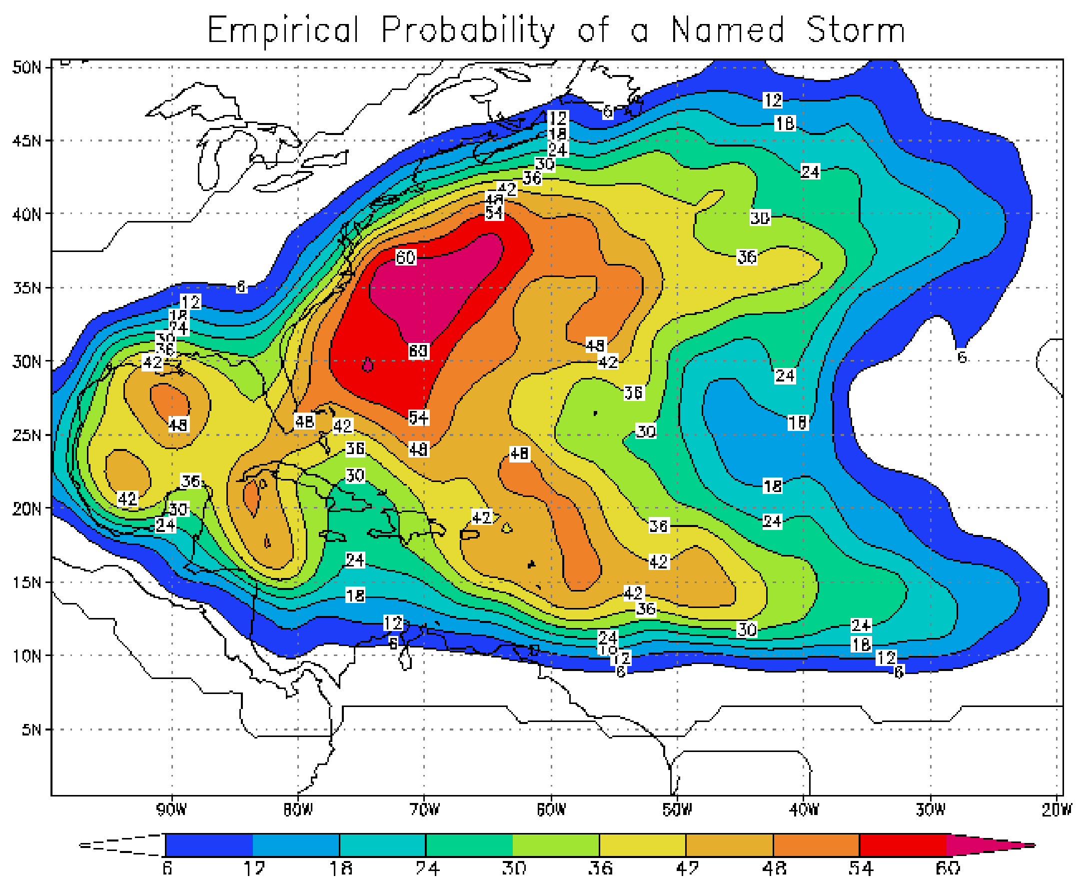

Figure 4.4 Probability that a named storm (tropical storm or hurricane) will affect any location during the Hurricane Season. Numbers on the chart represent the probability at that location. Source: Atlantic Oceanographic and Meteorological Laboratory (2002)

According to the United Nation's Intergovernmental Panel on Climate Change, "[i]ncreasing amounts of anthropogenic greenhouse gases may result in increased tropical sea surface temperatures … which could lead to more frequent and intense hurricanes, typhoons and severe tropical cyclones." Other experts, such as Houghton et al. 1996 and Henderson-Sellers et al. 1998, have noted that sea surface temperatures are only one part of the equation necessary for the development of tropical systems and that there is little reason to believe that global warming will *significantly* alter the characteristics of future storms. They summarize that:

- There is little evidence to suggest that there will be major changes in *where* tropical cyclones form or occur.

- There may be little significant change to the total *number* of tropical cyclones.

- The *peak intensity* (wind speed) of tropical cyclones may increase by five to 10 percent.

Increasing population densities combined with limited new construction of evacuation routes will significantly increase demand and congestion on roadways. Consequently, with a projection of the same or slightly stronger tropical cyclones, emergency managers will need to continue to expend resources on pre-storm evacuation planning and post-storm repair or cleanup activities.

4.3.3 Winter Storm Impacts on Emergency Management

Large winter storms, such as the blizzard of 1993 (i.e., the "Storm of the Century"), can cause widespread disruption to surface transportation systems. During this blizzard, roadway networks were shut down for days, impeding emergency response across a large portion of the country east of the Mississippi River. Major winter storms and blizzards can produce significant snow accumulation, blowing snow, reduced visibility, and dangerously low wind chill temperatures. The effects of long-term warming may slightly shift the track of future storms poleward. However, the frequency of winter storms and nor'easters may increase as the warmer subtropical atmosphere and Gulf Stream provide energy for storm initiation and growth. The net result is that emergency managers from the Rockies east to the mid-Atlantic coast may need to expend more resources preparing to handle disruptions caused by a higher frequency of these storms.

4.3.4 Wind Impacts on Emergency Management

Winds can disperse hazardous atmospheric pollutants, which pose risks to public safety. Emergency managers can utilize dispersion forecasts to predict where a plume of particulates will flow, and how pollutants will be diluted in the air. These forecasts can be used to predict the potential impact of nuclear or biological chemical releases. Output from dispersion models can be used to identify and delineate evacuation areas, warn communities at risk, and provide information on the level of protection required for response personnel involved in containment or cleanup activities. A gradual warming trend would promote the development of thunderstorms that could contain strong, gusty winds during a longer period of the year. These storms could complicate the prediction of plume trajectories and consequently make evacuation decision-making more difficult.

4.4 Traffic Management

Traffic management is affected most significantly by winter weather, severe storms, tropical cyclones, and low visibility. The following sections describe how these weather parameters impact operational practices.

4.4.1 Snow and Ice Impacts on Traffic Management

Wintry weather of any type can produce hazardous roadway conditions and can be a major impediment to effective traffic management. Snow, freezing rain, freezing drizzle and sleet can greatly increase crash risk. Even non-precipitation events such as black ice or roadway frost can greatly reduce vehicle traction and maneuverability. Traffic managers may employ control strategies (e.g., road, bridge, and ramp closures) in an attempt to mitigate some of these conditions. However, the result of wintry precipitation on roadways yields reduced roadway capacity and increased travel time delays.

As stated in earlier sections, there may be a net increase in freezing precipitation over certain parts of the country due to projected atmospheric warming. This may impact portions of the urban corridor in the northeast. An increase in the frequency of winter storms over the nation's mid section and east coast may also increase snowfall amounts. Traffic managers of the future would have to plan for the impacts of these possibilities.

On the other hand, a possible trend of warming may reduce the frequency of occurrence of wintry conditions from the Carolinas west across the Tennessee Valley and into the southern plains. In these localities, traffic managers would have to deal with a population that is not accustomed to driving in snow and ice. Traffic managers in these situations may need to restrict roadway access more often to minimize crash frequency.

4.4.2 Severe Storms Impacts on Traffic Management

Rain of any intensity can reduce pavement friction, decrease roadway capacity, and increase crash risk. On roads that have not had recent precipitation, light rain can mix with pavement contaminants (e.g., motor oil) decreasing pavement friction further. Vehicles entering areas of heavy rain can hydroplane or encounter slow or stopped traffic. Heavy rain can produce very low visibility, lane submersion, flooded underpasses, and damage to roadbeds. Hail and gusty winds, which can blow trees and power lines down, may also render roads impassible. Lightning can cause disruptions to power, communications, and control systems (e.g., traffic signal system, ramp gates).

An estimate of warming and the contrast in temperatures between warmer ocean waters and relatively cool land temperatures could lead to the formation of more thunderstorms that reach severe intensity, and extend the thunderstorm season. In order to prevent frequent congestion and delays, managers may need to utilize weather-related traffic signal timing and disseminate road weather information more frequently.

4.4.3 Tropical Cyclone Impacts on Traffic Management

Tropical cyclones can be a major challenge for traffic managers, who must coordinate with emergency managers to control cross-jurisdictional evacuation traffic before a hurricane and coordinate with maintenance managers to identify damaged infrastructure and detour traffic in the aftermath. To increase roadway capacity and traffic flow away from vulnerable areas, contraflow operations may be used on major freeway routes to guide vehicles out of designated evacuation areas quickly and efficiently, and the timing of traffic signals along major arterial corridors may be changed. After the storm, lanes may be submerged under water or obstructed by debris and there may be damage to roads, bridges, and other infrastructure. Traffic managers must also provide advisories and detour information to threatened populations. Projected warming could lead to the formation of the same or slightly more intense tropical cyclones in the future.

4.4.4 Low Visibility Impacts on Traffic Management

In low visibility conditions traffic managers disseminate advisories and regulations (e.g., "fog ahead reduce speed") to travelers to promote more uniform traffic flow, reduce traffic speeds, and reduce crash risk. In extremely low visibility, traffic managers may close roads and bridges or coordinate with emergency managers to guide traffic through foggy areas.

4.5 Road Users or Travelers

Travel decisions of road users are impacted primarily by wintry precipitation, low visibility, severe storms, and high winds. The effects of these weather parameters are discussed below.

4.5.1 Snow and Ice Impacts on Road Users

The occurrence of wintry precipitation can cause reduced road friction, loss of vehicle maneuverability, travel delays, and increased crash risk on roadways. In the presence of snow or ice, road users make travel decisions such as selecting vehicle type, installing special vehicle equipment (e.g., tire chains), and increasing following distance.

Future warming may reduce the amount and frequency of snow across central portions of the country and decrease the occurrence of ice frequency across portions of the Deep South. In addition, warmer atmospheric temperatures may cause mountain snows to occur at higher elevations. In some areas, the risk of snowstorms and nor'easters could increase due to greater temperature differences between the land and ocean. Portions of the interior mid-Atlantic region into New England may see more icing with an increase in coastal storms.

Road temperature also becomes important to commercial vehicle operators if their trucks exceed weight limitations imposed due to freeze/thaw cycles beneath roadbeds. This is most common for tractor-trailers that traverse the northern tier of the nation or travel in Alaska. In these regions, long periods of subsurface freezing or permafrost allow heavy vehicles to travel without damaging the underlying surface. However, during subsurface thawing road access to over-weight trucks may be restricted. A projection of warming could increase the number of freeze/thaw cycles across the northern tier and in Alaska for periods of the winter.

4.5.2 Low Visibility Impacts on Road Users

Reductions in visibility distance can produce variations in travel speed, which greatly increase the risk of chain-reaction crashes. Without information about the safe travel speed, each driver makes his or her own judgment, contributing to significant speed differences.

An estimate of future warming would probably not have much effect on fog formation in areas that typically experience reduced visibility. There may be a reduction in fog along the Atlantic and Gulf coasts due to the warmer water temperatures. However, the increased moisture content of the atmosphere may contribute to visibility restrictions elsewhere. Also, there is a possibility that warming could increase the frequency and intensity of heavy precipitation or wind blown dust, which could also impact visibility distance.

4.5.3 Severe Storm Impacts on Road Users

One of the greatest threats to public safety is driving a vehicle through moving water of unknown depth. Each year, many fatalities are attributed to floods from heavy rain, which can occur from localized storms to major cyclones. Prolonged heavy rain can produce flooding in underpasses and inundate entire road sections. Heavy rain in mountainous terrain may cause a sudden rise of water in small streams and creeks (known as flash flooding) that can overflow onto roads. The possibility of landslides, which can obstruct roadways, also increases during these torrents. Potential warming could increase the frequency of heavy rain as warm moist air surges north from the Gulf of Mexico and Atlantic Ocean.

4.5.4 Wind Impacts on Road Users

Strong winds can play a major role in vehicle operation. The buffeting of vehicles may decrease their stability and control, particularly in high-profile vehicles. In addition, high winds blowing across exposed roadways, elevated expressways or bridges may prevent these vehicles from crossing. Strong winds can blow snow or dust reducing visibility, and reduce fuel economy if blowing opposite the direction of travel. Finally, motorists have to avoid lane obstructions due to wind-blown debris. Estimated warming probably would not have a significant effect on wind patterns. Those areas that typically experience high-sustained winds (such as in the lee of the Rockies or across the central plains) would likely continue to experience them.

5.0 CONCLUSION

There is much speculation about how climate change will affect the weather over the nation. This paper used one scenario from the Environmental Protection Agency as a base to project how possible climate changes could impact surface transportation across the United States during the next century.

With a trend toward warming global temperatures, transportation managers may have to develop and implement mitigation strategies to deal with weather hazards. The following list summarizes some of the highlights of potential climate change:

- A gradually warming atmosphere may increase the frequency of ice (i.e., freezing rain and sleet) over portions of the Midwest and Northeast as precipitation, heated by warmer ocean temperatures, falls through cold air masses at the surface. This change may have significant effects on mitigation strategies used by maintenance managers, traffic managers, and road users.

- This same warming atmosphere may produce less snow over portions of the Southeast, the Tennessee Valley and the lower plains. However, the greater difference between land and water temperatures may lead to more winter cyclones that could bring periods of heavy snow, particularly to central and eastern portions of the nation. These changing snow patterns may produce problems in the south as transportation managers and motorists may be less familiar with safe and efficient operations under these conditions. Maintenance and traffic managers across northern climes may have to deal with a higher frequency of winter storms or nor'easters.

- Warming temperatures may change freeze/thaw cycles beneath roadways. This may induce infrastructure damage such as heaving or buckling. In areas where permafrost has been the norm, there may be periods where a thaw may necessitate access restrictions for truck traffic.

- The warming atmosphere may lead to a longer and more intense thunderstorm season. Transportation managers and road users will have to cope with the plethora of conditions that can occur with severe storms such as flooding rains, gusty winds, lightning and hail.

- Tropical cyclones may become slightly more intense with projections that the seasonal storm frequency may stay the same. With coastal populations increasing at a very fast rate, and limited new construction of evacuation routes, traffic and emergency managers will have to plan for better control strategies to manage evacuation traffic.

Today, the impacts of adverse weather on the roadway system are well recognized, and transportation agencies have successfully implemented advanced systems and strategies to respond to them. As the climate changes, there will be a need to continue this trend, modifying their operations to include the appropriate level of advisory, control and treatment strategies to limit the weather impacts on roadway safety and operations.

REFERENCES

1. Atlantic Oceanographic and Meteorological Laboratory (2002) "What Is My Chance of Being Struck by a Tropical Storm or Hurricane?", Hurricanes, Typhoons and Tropical Cyclones Frequently Asked Questions page, http://www.aoml.noaa.gov/hrd/tcfaq/G12.html.

2. Atlantic Oceanographic and Meteorological Laboratory (2002) "What May Happen with Tropical Cyclone Activity due to Global Warming?", Hurricanes, Typhoons and Tropical Cyclones Frequently Asked Questions page, http://www.aoml.noaa.gov/hrd/tcfaq/G3.html.

3. Covington, A. (2001) "UDOT Maintenance Crews Are Fighting Fog," Utah Department of Transportation Press Release, http://www.dot.state.ut.us/public/press_rel/Release%2000/Aug%20-%20Dec/R_283_00.htm.

4. Goodwin, L. and Pisano, P. (2002) "Best Practices for Road Weather Management," prepared by Mitretek Systems, Inc. for the FHWA Road Weather Management Program. http://www.ops.fhwa.dot.gov/weather/Publications/Case%20Studies/BP_RWM.pdf.

5. Henderson-Sellers, A., et al, (1998) "Tropical Cyclones and Global Climate Change: A Post-IPCC Assessment", Bulletin of the American Meteorological Society, 79, 19-38 http://www.aoml.noaa.gov/hrd/Landsea/IPCC/

6. Houghton, J., et al, (1996) "Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change," Climate Change 1995: The Science of Climate Change, Cambridge University Press, New York, p. 572.

7. Lawrence, D. (2000) "Innovations in Flood Warning: What's Happening in Dallas?", 12th Conference and Exposition of the Southwest Association of ALERT Systems, http://www.udfcd.org/saas2000/abstracts/Don%2Lawrence%20abstract.html.

8. Mitretek Systems (2001) "Surface Transportation Weather Decision Support Requirements (STWDSR): Needs Analysis for Traffic and Emergency Management, Preliminary Draft Version 3.0," prepared for the FHWA Road Weather Management Program.

9. National Center for Statistics and Analysis (2001) "Fatality Analysis Reporting System (FARS)" and "National Automotive Sampling System General Estimates System (NASS GES)", http://www.nhtsa.dot.gov/people/ncsa/fars.html.

10. National Climatic Data Center (2000) "Climate Atlas of the Contiguous United States, Disk 1, Contiguous U.S.", Product Development Branch, National Oceanic and Atmospheric Administration.

11. Owens, M. (2000) "The Advanced Transportation Weather Information System (ATWIS)," University of North Dakota, http://www.ctre.iastate.edu/pubs/midcon/oens.pdf.

12. PBS&J, (2000) "Southeast United States Hurricane Study Technical Memorandum No. 1 – Final Report," http://www.fhwaetis.com.

13. Perrin Jr., J., et al. (2001) "Modifying Signal Timing during Inclement Weather," University of Utah, http://ops.fhwa.dot.gov/Weather/Publications/WxRelatedTiming.pdf.

14. Pisano, P. and Goodwin, L. (2002) "Surface Transportation Weather Applications," FHWA Office of Transportation Operations in cooperation with Mitretek Systems, Inc.

15. Rice, Jr., et al (2000), "Avalanche Hazard Reduction for Transportation Corridors Using Real-time Detection and Alarms," University of Utah in cooperation with the Idaho Transportation Department and the Wyoming Department of Transportation, http://www.sicop.net/annals-paper%20total.pdf.

16. Spradling, R. (2001) "CHP 'PACE' Program," District 10 Press Release, Caltrans, http://www.dot.ca.gov/dist10/pr01.htm.

17. U.S. DOT Analysis and Information Online (2002) "Motor Carrier Management Information System (MCMIS) Crash File," http://ai.volpe.dot.gov/CrashProfile/datasource.asp

18. U.S. DOT (2001) "Intelligent Transportation System (ITS) Projects Book," ITS Joint Program Office, p. 285, http://www.itsdocs.fhwa.dot.gov/jpodocs/EDLBrow/@@_01!.pdf.

19. U.S. Environmental Protection Agency (2002) "Global Warming – Climate" http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ClimateFutureClimateUSClimate.html

20. U.S. Environmental Protection Agency (2002) "Global Warming – State Impacts", PDF files available for each state at http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ImpactsStateImpacts.html