Weather and climate change implications for surface transportation in the USA

by Marjorie McGuirk[1], Scott Shuford[2], Thomas C. Peterson[1] and Paul Pisano[3]

Introduction

Weather affects the operation of the transportation systems that we all rely on—from automobiles slowed by a wet surface, to delivery trucks delayed by high winds, to passenger trains stalled by ice and snow. Daily operational decisions in the transport sector, such as the amount of cargo that a plane or a barge can safely handle, must take weather conditions into consideration.

Climate, on the other hand, affects transportation infrastructure. Railways, ports, piers, highway culverts, bridges and other transportation infrastructure have been optimized for the expected range of weather conditions that we call "climate." When the weather becomes more extreme—more outside the bounds of what is considered "normal" climate—the transportation infrastructure becomes less reliable and less safe. Rising sea level and more intense flooding affect the safety and functionality of bridges and trestles. Higher temperatures buckle railroad tracks and roadways.

Figure 1 — Kansas City downtown airport, Interstate Highway 70 and the Kansas City Port: a broad mix of transport options

Stronger tropical cyclones inundate and damage transportation infrastructure, resulting in delayed delivery of goods and services.

Adverse impacts to transit time, delivery reliability and efficiency in turn affect the cost of all goods transported by these systems. Another economic cost involves the retrofitting of infrastructure to adapt it to the new climate, including more resilient or relocated transportation facilities in areas subject to tropical cyclones, bridges and trestles with higher clearances to address flooding and sea-level rise, and heat-resistant highway and rail design.

Changes in the weather require adjustments to daily operation of transportation systems, while climate change requires adjustments to transportation infrastructure. Society is accustomed to delays in airline travel resulting from snow, rain or fog, but is less prepared for the significant investment required to adapt transportation infrastructure to climate change. This article explores the projected extent of

1 National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, North Carolina, USA. E-mail: Marjorie.McGuirk@noaa.gov

2 University of North Carolina, Asheville, North Carolina, USA

3 Federal Highway Administration, Washington D.C. E-mail: Paul.Pisano@dot.gov

the impacts of climate change on transportation infrastructure, with a focus on the USA.

Methodology

This article draws heavily upon previous studies including *Potential Impacts of Climate Change on US Transportation* and *Climate Variability and Change with Implications for Transportation*, both commissioned by the National Research Council and published in 2008 (NRC, 2008; Peterson, 2008). In-depth assessments of major US metropolitan areas with highly developed transportation systems were part of these references. This article attempts to add more recent analysis and foresee what the most far-reaching impact of climate change on transportation might mean in the human context.

This article includes information imparting a basic understanding of the weather conditions that affect day-to-day operations of surface transportation by road, rail and water. The methodology was to identify the weather parameters that matter most to transportation and use the model values to understand how those parameters might change in the future.

Identification of climate change impacts on transportation involved the use of a number of Climate Change Science Plan assessments. In order to restrict the number of weather parameters, we analysed those that have some relevance for climate variability and change. For example, while a tornado would have a huge impact on transportation, there is little confidence associated with the relationship between the frequency or intensity of tornadoes and climate change, thus tornado impacts are not included here. We included variables for which there are positive and negative impacts on transportation.

Although this article is focused on impacts to transportation in the USA, the techniques are applicable elsewhere.

Weather impacts on surface transportation

Travellers' advisories, issued by the National Weather Service when transportation-sensitive conditions may occur, necessarily vary by geographical area. A trace of snowfall would trigger a traveller's advisory in the southern portions of the USA, but several centimetres of snow would be

The weather parameters, a categorization of weather advisories based on those parameters, and their impacts on transportation

Weather parameters	*Category*	*Impacts*
Precipitation elements	Freezing precipitation, snow accumulation, liquid precipitation, precipitable water vapour, soil moisture, flooding, water body depths, fire weather	Loss of traction and control, delays, reduced speeds, stresses on vehicle components and tyres, rules on tyre chains, wet road surface, road spray, flooding causing road closures, re-routeing, weak and uneven braking, intermodal impacts, softened railroad beds, roadbed scouring; drought causing risk of dust and smoke reducing visibility, highway closures, intermodal impacts from barge shutdowns
Thunderstorm-related	Severe storm cell tracks, lightning, hail, straight line winds (derechos)	Acute, rapidly changing conditions with multiple risks of collisions and damage from loss of control, impaired visibility; rock slides causing risk of collisions and delays, damage to infrastructure, blocked railroads
Temperature-related	Air and surface temperature, including maximum and minimum, first occurrence of season, heat index, cooling or heating degree days	Stresses on vehicle components, infrastructure and, at high temperature, perishable cargoes, rail buckling (sun kinks), reduced speeds on rails
Winds	Wind speed	Vehicle instability, loss of control, blow-overs
Visibility	Restrictions from fog, haze, dust, smog and sun glare, upper atmosphere restrictions from volcanic and desert dust	Reduced speed, risk of collisions and damage from rapid change
Sea state	Tropical cyclones including tracks and elements affecting evacuation routes, open-water sea ice, high surf, storm surge, abnormal high or low tides, freezing spray, hurricane winds, sea state, flooding, wind wave height, sea wave height	Supply chain disruptions, road closures, extensive damage to infrastructure and vehicles, obstructions blocked rails; sea-level rise causing rises in sea levels, risk and damage to infrastructure, changes in agricultural and manufacturing production and shipments

the threshold for an advisory in the northern regions, where drivers are accustomed to snowy conditions.

Since about one-quarter of transport delays and crashes in the USA are due to adverse weather, the need for region-specific types of surface weather information is re-assessed regularly. Identifying the transportation-sensitive weather parameters was aided by Weather Information for Surface Transportation—National Needs Assessment Report, henceforth called WIST (Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), 2002).

Weather parameters, arranged by category of weather advisories, are grouped in the table on the previous page, along with their impacts. (Rossetti, 2002 and 2008.)

The WIST report established the national needs and requirements for weather information associated with decision-making for surface transportation operations in six different sectors: road; long-haul railway; marine transportation; rural and urban transit; pipeline systems; and airport ground operations. Here, we will take a look at railway, roadway and marine transport and the impacts of the two dominant weather factors: extreme temperature and extreme precipitation.

Weather research and surface transport

Decision-support tools for road management rely heavily on accurate observations and predictions of a wide variety of weather events, including fog, heavy rainfall, snow, sleet, freezing rain, forest fires and smoke, sandstorms and blowing and drifting snow. Recent decades have seen a dramatic increase in our ability to both observe and predict these events across a variety of timescales. For example, conditions conducive to ice and snow build-up can now be detected by sensors embedded in roadways and the onset, severity and duration of some major snowstorms have been predicted with several days of lead-time (Pisano, 2004).

Major safety problems still occur, even when relying on accurate use of the world's best forecast models. WMO's World Weather Research Programme is focused on accelerating improvements in the prediction of high-impact weather from timescales of a few hours to two weeks. Several projects have direct applicability to surface transportation, such as the THORPEX (The Observing System Research and Predictability Experiment) programme efforts to extend predictions of major precipitation events into week 2, the Sand and Dust Storm Warning, Assessment and Advisory System and nowcasting of heavy rainfall (see: http://www.wmo.int/pages/prog/arep/wwrp/new/thorpex_new.html).

Extreme temperature

Railways face particular impacts from high temperatures. When railways opened in the American West 150 years ago, the technology of steam-operated trains required regular refuelling with water about every 160 km. Forts, then towns, grew up around these refuelling stations. Today, those towns, now grown into cities, stretch across the country in lines running from east to west.

Today, track is designed to withstand the internal stresses resulting from a large temperature change. However, if heated up beyond the design criteria, thermal misalignments or track buckles may result and derailments are possible. Neutral temperature, generally set when the rail is laid, is the point where rail is neither expanding nor contracting. This neutral temperature is generally designed to be about 22°C less than the maximum expected rail temperature.

Some research cited by the WIST report shows track failure can occur at ambient temperatures above 43°C, depending on the degree of

Figure 2 — Barge transportation on the Mississippi River and river bank infrastructure exposed to significant long-term changes in river level

difference from the neutral installation temperature. Track-alignment problems were a significant cause of accidents from weather-related factors, with about seven major sun-kink events a year (Rossetti, 2002).

Operational measures to adapt to weather-related temperature extremes include lower speeds and shorter trains to shorten braking distances and lighter loads to reduce track stress. These adaptations affect the efficiency of railway operations, increasing the per unit cost of transport.

Sustained high temperatures can also affect highways and bridges. Materials used in constructing roads have a limited range of heat tolerance before thermal cracking occurs. Although road-surface temperature may significantly exceed ambient temperature, air temperature over 32°C is a significant threshold for roadways. A prolonged heatwave in July 2000 in the San Francisco Bay area shut down Interstate 80 when three lanes buckled due to thermal expansion.

Prolonged heat beyond the design criteria can also cause premature deterioration, shortening the service life of roads. In the Alaska region, higher temperatures have thawed permafrost, weakening or destroying roadbeds built upon previously frozen ground. Bridges can be particularly subject to extra stresses from extended periods of elevated temperatures. Additionally, according to WIST, high road surface temperature increases the risk of tyre blow-outs, especially in heavily loaded vehicles.

These heat-related effects on transportation will require short-term operational and long-term infrastructure adaptations to avoid safety and transport efficiency problems. Highway freight transportation has significantly increased over the past 30 years to accommodate "just-in-time" delivery of goods, in effect turning the interstate highway system into America's warehouse (Shuford, 2009).

Weather-related delivery delays acquire added meaning when traditional, non-motorized warehousing of goods is limited. For example, local food shortages due to delivery delays resulting from inclement weather are a concern. Just-in-time delivery and a new inland port were the impetus behind new networks of the Roadway Weather Information Systems (RWIS) as described in the Kentucky mesonet workshop (Foster, 2008). As the name implies, these stations measure weather conditions alongside roads, as well as other transportation corridors.

In at least one instance, however, higher temperatures may have a significant positive impact on transportation. If Arctic Ocean ice conditions continue to become less severe, prospects are for increased international trade through Alaskan water via the Northern Sea Route (NRC, 2008). A strong negative trend in summertime Arctic sea-ice extent has been observed over the past 30 years, which was further reinforced by observations in September 2008. According to a report from the National Oceanic and Atmospheric Administration (NOAA), it is becoming increasingly likely that the Arctic will change from a perennially ice-covered to an ice-free ocean in the summer (Richter, 2008). This will have great impact on the preferred routes for major oceanic transportation.

Extreme precipitation

Precipitation accounts for most of the delays and crashes in motor vehicles where weather is a cause. Rain of sufficient intensity and duration can submerge roads and flood low-lying underpasses. Flooding causes road scouring and washout. Flooding damages or softens railbed support structures, causes overflow onto tracks and mudslides that damage tracks, with about seven major events a year (Rossetti, 2002).

Major precipitation events can disrupt the entire surface transportation system, including goods transported by train, truck, ship and barge. For example, in January 2009, intense precipitation—amounting to 15 cm, coupled with a warm spell that melted snow—brought freight trains to a standstill and stranded hundreds of trucks along the major highways near

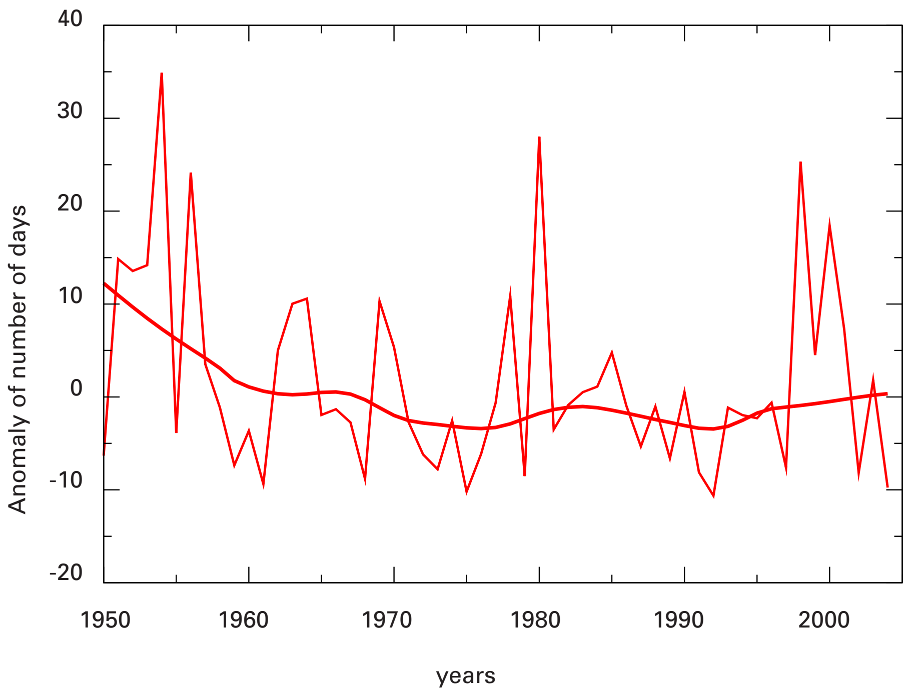

Figure 3 — Historical time series from stations within 500 km of Dallas, Texas, showing anomalies of the number of days above 37.7°C

Seattle, Washington. A 30-km stretch of Interstate 5, the state's major north-south freeway, closed. The event was so massive that alternative routes, both for roadways and railways, were also closed by widespread avalanches, mudslides and flooding, isolating a major port city from its markets in the rest of the country (various media reports).

A record-breaking 24-hour rainstorm in July 1996 resulted in flash flooding in Chicago. Extensive travel delays occurred on metropolitan highways and railroads, commuters were unable to reach Chicago for up to three days and more than 300 freight trains were delayed or re-routed. Chicago is the nation's rail hub, with nearly 90 per cent of all freight traffic going through

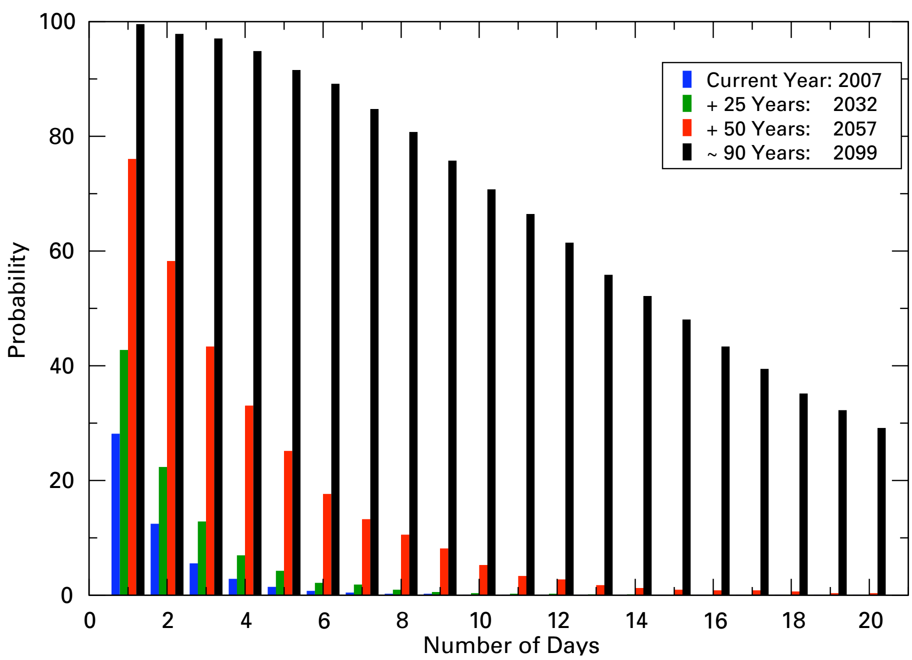

Figure 4 — The current and future probability of having one to twenty days during the summer at or above 43.3°C at Dallas, Texas

it (Changnon, 1999). Rail and road undercutting from events like these could lead to permanent closures of some infrastructure (NRC 2008).

Because intense precipitation events can result in flooding that damages or destroys transportation-related infrastructure, civil engineers use precipitation intensity-frequency-duration values when designing road culverts, stormwater drainage systems, rail lines and roadbeds. Probabilistic estimates of rainfall intensities for a range of durations (5 minutes to 24 hours) for return periods or recurrence intervals of 20, 50 and 100 years, are typical design criteria.

For much of the country, these probabilistic estimates of precipitation date from the 1960/1970s. Often, structures are engineered to withstand a 100-year flood (a flood for which there is a 1 per cent chance of occurrence in any given year). The flood zone maps promulgated by the Federal Emergency Management Agency (FEMA) are based largely on older precipitation intensity-frequency-duration estimates. In many regions, the area affected by an actual 100-year flood will be greater than would be expected using FEMA maps based on this out-of-date information. Consequently, structures engineered to those standards may be at risk. More recent analyses (http://www.nws.noaa.gov/oh/hdsc/) provide better estimates on which to base design decisions (Bonnin, 2003).

At the other extreme, precipitation deficits cause lower water levels which adversely affect the use of inland waterways, particularly for barge traffic. Drought has had an influence on commercial navigation on the lower portion of the Mississippi River from St Louis to the Gulf of Mexico, where there are no locks and dams to maintain navigation depths. The 1988 drought stranded over 4 000 barges. As a result, railroads saw increased business in hauling grains and other bulk commodities.

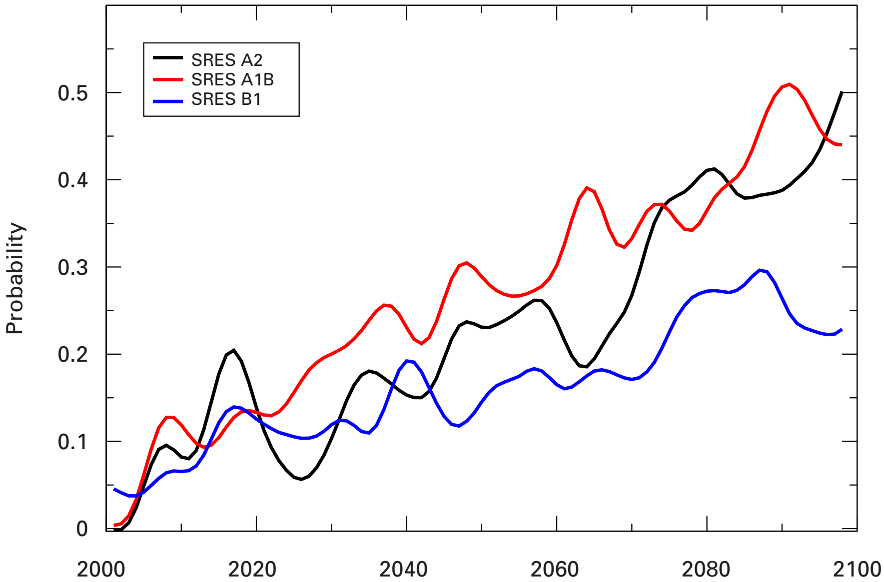

Figure 5 — The upward trend in the Simple Daily Intensity Index (the total precipitation per year divided by the number of days with precipitation) indicates that, on a US area-averaged basis, when precipitation does occur, it tends to be heavier. Median model projected changes in the Simple Daily Intensity Index is projected to continue to increase over the continental USA in the future.

balance, however, because systems are adapted to their historical range of extremes, the majority of the impacts of events outside this range are expected to be negative (CCSP SAP 3.3).

In all transport sectors, weather extremes affect the efficiency of operations and safety and integrity of the infrastructure. Previous sections described weather-related transport impacts from extreme high temperature and extreme precipitation events. As the following discussion indicates, these events are expected, with high confidence, to occur more frequently in the future because of climate change. Additionally, some of the most significant regional transportation infrastructure vulnerabilities to climate change will occur in coastal areas.

Climate-change impacts on surface transportation

Climate change will affect the efficiency, safety and reliability of existing transportation infrastructure and the design of new infrastructure. Retrofits and new designs will be expensive to implement, so sound climate data are essential to good decision-making. The climate projections used in the NRC study were based on both observational data and model output, using several different techniques. While a full description can be pursued through the references, the global climate model output used were those that contributed to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). For this study, three greenhouse-gas emissions scenarios were analysed and compared to model simulations of the recent past.

This article does not reproduce the full list of parameters and impacts on surface land and water transportation. They are available in the annex to the NRC report (pages 117-134). Instead, a simple list of the key phenomena likely to undergo change with global warming affecting transport is provided in the box overleaf.

The primary way that climate change can impact transportation is through changes in extreme weather conditions. As noted, there are some positive impacts. On

Temperature projections

The climate model output provides projections for changes in mean temperature. But how do these changes in mean temperatures predict extreme temperatures that may result from climate change? The programme of NOAA's National Climatic Data

D. McGuirk

Figure 6 — Roads are increasingly subject to heavy traffic. With more high-impact weather, traffic planners will need to find ways of dealing with climate change.

Key phenomena likely to undergo change with global warming affecting transport

- **Less very cold weather**
  - Easier maintenance in snow free areas
  - Positive impact on marine transportation
  - Fewer ice jams
  - Less ice build-up on decking
- **More very hot weather**
  - Railroad track buckling
  - Highway asphalt rutting
- **General warming would contribute to:**
  - Melting Arctic sea ice:
    - In summer only
    - Potential opening of North West passage (northern sea route)
    - Europe to the Far East could save 4 000 km
  - Thawing permafrost problems for Alaskan roads and pipeline
  - Decreased seasonal icy roads and frozen rural roads
- **Increasing heavy rain events**
  - Delays in many forms of transportation
  - Localized flooding
  - Damage to bridges designed to last 100 years
  - Damage to roads and railways designed to last 25 and 50 years
  - Scouring of pipeline roadbeds
- **Projected increased summer drying and likelihood of drought**
  - Low water levels may hamper inland barge traffic
  - General warming leading to:
    - Longer rain and shorter snow seasons
    - Positive impact on transportation, particularly roadway safety

Center (NCDC) Probabilities of Temperature Extremes in the USA (NOAA, 1999 (CD ROM)) was used to estimate the probability that a threshold temperature will occur for one or more consecutive days and/ or the probability that a threshold temperature will be exceeded for any number of days for a station in a given month or season, based on statistics from the observed climate combined with model projections.

The city of Dallas, Texas, offers an example of how more frequent high temperatures might affect rail transportation. As noted earlier, the threshold of 43°C is the point at which rail buckling could occur and rail transport would be negatively affected. Dallas recorded a temperature of 43°C in September 2000 and three times in the summer of 1980 (spike in Figure 3). Figure 4 shows that Dallas, like most of the USA, has projections that indicate that the probability of having a hot summer day will be increasing, i.e. the temperature at which rails buckle will become an increasingly common occurrence.

As a consequence, we can reasonably expect that extensive infrastructure retrofits will be necessary to ensure continued efficiency, safety and reliability of the US transportation system in the face of heat extremes resulting from climate change.

Precipitation projections

With projected changes in total annual precipitation in the USA having considerable uncertainty, indications are that this precipitation, when it falls, will occur during fewer, more intense events. (CCSP SAP 3.3). Figure 5 is a simple daily intensity graph. It is the total precipitation in a year divided by the number of days with precipitation. It has a clear upward trend, which is borne out by the following examples of precipitation events that affect transportation.

An analysis of precipitation events in the Mississippi Delta region (Burkett, 2002) shows increases in more intense events (rainfall greater than 5 cm per day). Average annual precipitation has increased overall here by 20-30 per cent over the past 100 years. More recent years have had more intense precipitation over much of the USA (NRC, 2008). A larger share of rainfall is occurring on very wet days (defined as an incident in the upper 95 per cent of probability of occurrence). Increases in intense precipitation in the warm season in the central USA have been observed, with large amounts of rain falling over a shorter period of time.

Some 65 000 km of navigable waterways along the coasts, rivers and lakes in the USA facilitate transportation by ship and barge. An extensive study of the states of Mississippi, Missouri and Ohio, which have complex riverine transportation systems, reveal a climatic shift to more multi-day periods of heavy rain since the 1920s and a systematic, long-term increase in both flood incidence and magnitude (Changnon, 2001). Given that half the grain exported from the USA is carried on barges in this river system, such climatic shifts have great impact.

Figure 8 — Advanced systems monitor US highways and rivers to manage traffic more effectively during high-impact weather.

Coastal impacts

Tropical and extra-tropical storms have great impact on transportation infrastructure in coastal regions. Transportation systems of the New York-New Jersey-Connecticut metropolitan regions have been shown to be vulnerable to significant extra-tropical cyclones or nor'easters (Peterson, 2008). For example, the nor'easter of December 1992 severely crippled the transportation systems throughout the area. Roadways were flooded; trains were delayed or cancelled and bus services cancelled; airports were closed due to high winds; piers, marinas and roads were destroyed by coastal flooding and surf that driven by hurricane-force winds and exacerbated by astronomical high tide; thousands of boats were destroyed or significantly damaged (NOAA, 1992).

The Metro New York Hurricane Transportation Study (MNYHTS, 1995), undertaken following the extra-tropical storm of December 1992, provides an excellent assessment of transportation infrastructure impacts by computing storm-surge heights associated with worst-case storm tracks for hurricanes. Sixteen important transportation infrastructures, including tunnels, bridges, marine terminal facilities and John F. Kennedy International Airport were examined, noting their lowest critical elevations. All the structures' critical elevations were below the surge level of Category 3 and 4 hurricanes modelled under present climate conditions. In the model, airfields, entry to tunnels, bridge approaches and ventilation shafts of subways were all swamped by the storm surge. Similar or more intense events, magnified by the effects on critical elevations from sea-level rise resulting from climate change, only worsen the potential for widespread damage in the future.

More frequent flooding of highways and railroads near estuaries during high tides and storms may be experienced as sea level rises. Port operations, especially the movement of goods from one mode of transport to another (ship to rail to truck), will be hampered (WIST 4-27). The clearance above high water will gradually diminish for rail and road bridges across water in the tidal zone (NRC, 2008). Many east coast railroads have been in their present location for 150 years, a period during which global and local sea level has risen and many tracks, signals and stations are already low enough to be flooded during severe storms (Titus, 2002).

Several studies conducted for coastal areas along the Gulf and Atlantic coasts having important transportation infrastructures, make estimates of areas likely to be below sea level at time frames of 25, 50 and 100 years (NRC, 2008). These estimates show that important transportation infrastructure will be permanently inundated, barring mitigation techniques such as the building of defensive barriers like sea walls.

The impact of local sea-level rise is affected by local conditions such as subsidence, changes in the shoreline's shape, saltwater intrusion and inland precipitation flooding. Storm-surge calculations should be performed on top of projected local sea-level rise and take into account the lowest critical elevation of infrastructure near the coast. That, coupled with the possibility of more intense tropical cyclones (CCSP SAP 3.3) would give a better view of the local impacts. Damage to inland structures, including transportation infrastructure, is largely dependent on the storm-surge elevation, exacerbated by the amount of local sea-level rise as the following example indicates.

The area of a 100-year flood on today's maps for Hampton Roads, Virginia, the nation's 39th most populous metropolitan statistical area, becomes a 50-year return period as a consequence of higher rainfall intensity and storm surge from storm events (Shen, 2005). Tide gauges in the nearby Chesapeake Bay indicate sea-level rise in this area is twice the global average due to local conditions. The area is home to the largest naval base in the world, two civilian airports, a military transportation control centre and several military bases, employing over 100 000 people. Connected by extensive bridge and tunnel networks to the second largest cargo port on the east coast, this critical transportation infrastructure is all located within inundation areas from local sea-level rise at the high-probability mean scenario.

Many structures on the ocean coast are designed for a working economic life of 50 years or less. A list of these structures includes airports, levees and canals, seaports, port structures, navigation channels, turning basins, docking areas and navigation gates, piers and wharfs, dray and wet docks, highways, railroads, vehicular tunnels and bridges, storm drains, pipelines and upstream flood-control systems. For this infrastructure, relatively frequent repair, replacement, and re-design can take into account local sea-level rise (Peterson, 2008; Titus 2002).

Nevertheless, transportation infrastructure can influence patterns of development of coastal regions far beyond the life cycle of the road, or rail, or bridge, thus the ability of coastal regions to adapt to climate change may be helped or hindered by the decisions that transportation officials make today (Titus 2002). Infrastructure planners would benefit from taking climate projections into consideration when making decisions about new infrastructure, including the placement of this infrastructure in less vulnerable locations (Shuford, 2008). For example, Virginia Inland Port, some 350 km inland, serves as a redistribution centre for moving goods from one mode of transport to another, reducing some dependency on at-risk coastal marine terminals.

Conclusion

The impact of weather events on transportation operations and the impact of climate change on transportation infrastructure will be significant, as weather extremes change in both frequency and intensity. Weather-related operational information will be critical to minimize delivery delays and to improve transportation safety, reliability and efficiency.

As we become more certain, identification of climate-change impacts for local conditions provides infrastructure planners with the best possible information they need to reduce risk and improve efficiency and reliability of new and retrofitted transportation systems.

Impacts on coastal infrastructure may be the most significant owing to two particular factors. First, coastal areas are subject to the effects of sea-level rise and stronger tropical and extra-tropical storms. Second, it is at the coasts that three critical modes of transportation interconnect: ships, trains and trucks all carry goods to and from ports.

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