# 5. Transportation

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**Key Messages:**

1. **The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are reducing the reliability and capacity of the U.S. transportation system in many ways.**
2. **Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.**
3. **Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.**
4. **Climate change impacts will increase costs to transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.**



The U.S. economy depends on the personal and freight mobility provided by the country's transportation system. Essential products and services like energy, food, manufacturing, and trade all depend in interrelated ways on the reliable functioning of these transportation components. Disruptions to transportation systems, therefore, can cause large economic and personal losses. The national transportation system is composed of four main components that are increasingly vulnerable to climate-change impacts:

- Fixed node infrastructure, such as ports, airports, and rail terminals
- Fixed route infrastructure, such as roads, bridges, locks, canals/channels, railways, and pipelines, mostly publicly owned and/or managed
- Vehicles, such as cars, buses, and trucks; railcars and locomotives; ships and barges; and aircraft – all mostly privately owned
- The people, institutions, laws, policies, and information systems that convert infrastructure and vehicles into working transportation networks

Transportation systems influence future climate characteristics and are also affected by changes in the climate. In 2010, the U.S. transportation sector accounted for 27% of U.S. greenhouse gas emissions (also called heat-trapping gas emissions) (Source: EPA 2011). Petroleum accounts for 93% of the nation's transportation energy use (EIA 2011), while cars and trucks account for 65% of transportation emissions (EPA 2011).

Transportation systems are already experiencing costly climate change related impacts. Many inland states – for example, Vermont, Tennessee, Iowa, and Missouri – have experienced severe precipitation events and flooding during the past three years, damaging roads, bridges, and rail systems. Over the coming decades, all modes and regions will be affected by increasing temperatures, more extreme weather events, and changes in precipitation. Concentrated transportation impacts are likely in Alaska and along seacoasts.

Transportation systems require expensive and long-lived (typically 50 to 100 years) infrastructure. The estimated value of U.S. transportation facilities in 2010 was $4.1 trillion (U.S. Bureau of Economic Analysis 2011). As climatic conditions shift, portions of this infrastructure will increasingly be subject to climatic stresses that will reduce the reliability and capacity of transportation systems (NRC 2008). Transportation systems are also vulnerable to interruptions in fuel and electricity supply, as well as communications disruptions – which are also subject to climatic stresses (NRC 2008). Power outages resulting from Hurricane Katrina shut down three major petroleum pipelines for two days, and the systems operated at reduced capacities for two weeks (Wilbanks et al. 2012) .

Climate change will affect transportation systems directly, through infrastructure damage, and indirectly, through changes in trade flows, agriculture, energy use, and settlement patterns. If, for instance, corn cultivation shifts northward in response to rising temperatures, U.S. agricultural products may flow to markets from different origins by different routes (Vedenov et al. 2011). If policy measures and technological changes reduce greenhouse gas emissions by affecting fuel types, there will likely be significant impacts on the transportation of energy supplies (pipelines, coal trains, and so on) and on the cost of transportation to freight and passenger users (CCSP 2008).

Disruptions to transportation system capacity and reliability can be partially offset by adaptations. Transportation systems *as networks* may use alternative routes around damaged elements or shift traffic to undamaged modes. Other adaptation actions include: new infrastructure designs for future climate conditions, asset management programs, at-risk asset protection, operational changes, and abandoning/relocating infrastructure assets that would be too expensive to protect.

## *Reliability and Capacity at Risk*

**The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are reducing the reliability and capacity of the U.S. transportation system in many ways.**

Global climate change has both gradual and extreme event implications. A gradually warmer climate and increased drought in the Southeast and the Southwest will affect slope stability and cause pavement buckling that will damage infrastructure like roads and rail lines. Streamflows based on increasingly more frequent and intense rainfall instead of slower snowmelt could increase the likelihood of bridge damage from faster-flowing streams. However, less snow in some areas will reduce snow removal costs and extend construction seasons. Shifts in agricultural production patterns will necessitate changes in transportation routes and modes.

Climate models project that extreme heat and heat waves will become more intense, longer lasting, and more frequent. By 2080-2100, average temperatures are expected to increase by 3°F to 6°F for the continental U.S., assuming emissions reductions from current trends (B1 scenario), while continued increases in emissions (A2 scenario) would lead to an increase in average temperatures ranging from 5°F in Florida to 9°F in the upper Midwest (Kunkel et al. 2012a).

The impact on transportation systems not designed for such high temperatures would be severe. Expansion joints on bridges and highways are stressed and asphalt pavements deteriorate more rapidly at higher temperatures (Meyer et al. 2010). Rail track stresses and track buckling will increase (Hodges 2011; Rossetti 2002). Lift-off limits at hot-weather and high-altitude airports will reduce aircraft operations (Kulesa 2003).

Construction crews may have to operate on altered time schedules to avoid the heat of the day, with greater safety risks for workers (NIOSH 1986). The construction season may lengthen in many localities. Similarly, higher temperatures (and precipitation changes) are likely to affect transit ridership, bicycling, and walking in various ways.

Climate change is most severe at high northern latitudes. Alaska has experienced a 3°F rise in average temperatures since 1949 (Stewart et al. 2012), double the rest of the country. Winter temperatures have risen by 5°F. On the North Slope, sea ice formerly provided protection to the shoreline against strong fall/winter winds and storms. Retreating ice reduces this protection, eroding the shoreline and endangering villages. Thawing permafrost is causing pavement, runway, rail, and pipeline displacements, creating problems for operation and maintenance, and requiring reconstruction of key facilities. Arctic warming is also projected to allow the seasonal opening of the Northwest Passage to freight shipment (Arctic Council 2009).

**Box 1: Thawing Alaska**

Permafrost – soil saturated with frozen water – is a key feature of the Alaskan landscape. *Frozen* permafrost is a suitable base for transportation infrastructure such as roads and airfields. In rapidly warming Alaska, however, as permafrost thaws into mud, road shoulders slump, highway cuts slide, and runways sink. Alaska currently spends an extra $10 million per year repairing permafrost damage (Adaptation Advisory Committee 2010).

A recent study, which examined potential climate damage to Alaskan public infrastructure using results from three different climate models (Larsen 2007), considered 253 airports, 853 bridges, 131 harbors, 819 miles of railroad, 4,576 miles of paved, and 5,000 miles of unpaved road that could be affected by climate change. The present value of additional public infrastructure costs due to climate change impacts was estimated at $5.6 to $7.6 billion through 2080, or 10% to 12% of total public infrastructure costs in Alaska, which might be reduced by 40% with strong adaptation actions (Larsen 2007; Larsen et al. 2008).

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Impact of Sea Level Rise and Storm Surge on Mobile, Alabama

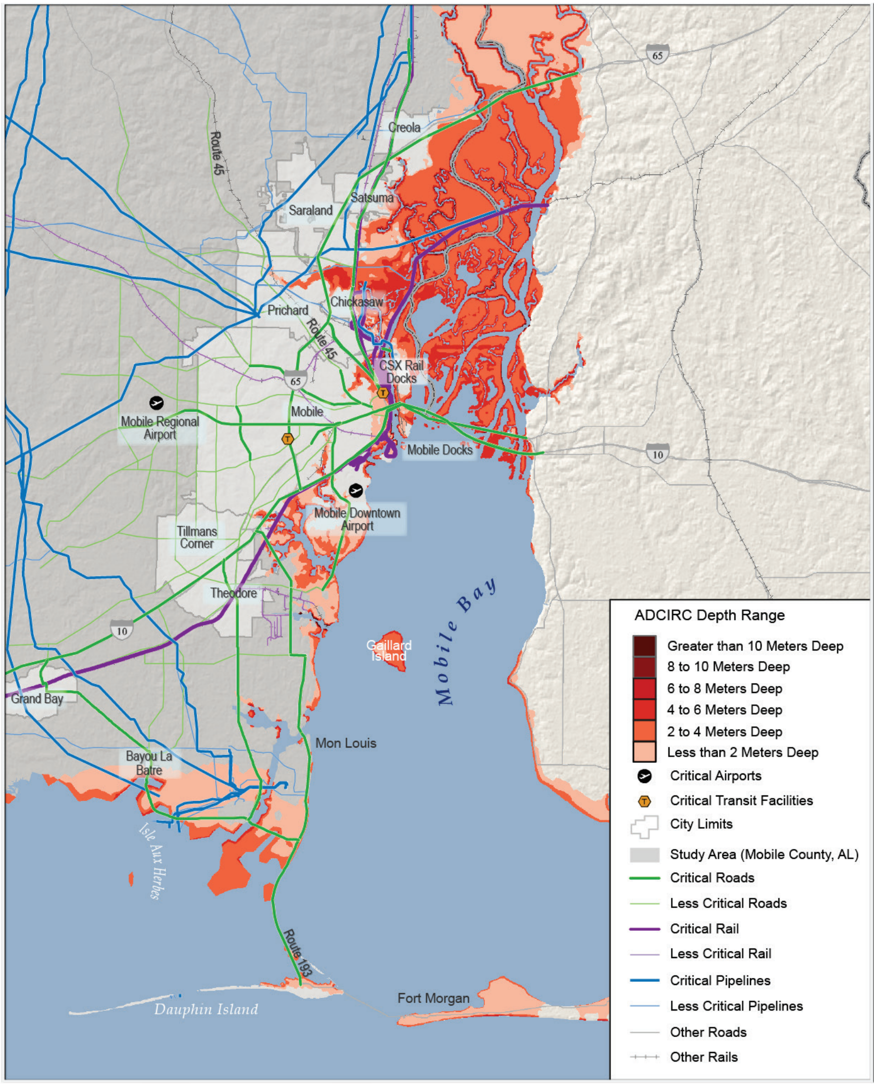


**Figure 5.1:** Impact of Sea Level Rise and Storm Surge on Mobile, Alabama

**Caption:** Many coastal areas in the U.S., including the Gulf Coast, are especially vulnerable to sea level rise impacts on transportation systems. This map shows that many parts of Mobile, Alabama, including critical roads, rail lines, and pipelines, would be exposed to storm surge under a scenario of a 30-inch sea level rise combined with a storm similar to Hurricane Katrina. A 30-inch sea level scenario is within the range projected for global sea level rise (Ch. 2: Our Changing Climate, Key Message 9). (Source: DOT 2012).

## *Coastal Impacts*

**Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.**

The transportation impacts of rising sea levels, which are expected to continue rising by an additional 1 to 4 feet in this century (See also Ch. 2: Our Changing Climate, Key Message 9) (NCA/SLCS Team 2011), will vary widely by location and geography. When sea level rise is coupled with intense storms, the resulting storm surges will be greater, extend farther inland, and cause more extensive damage. Ports and harbors will need to be reconfigured to accommodate higher seas. Many of the nation's largest ports are along the Gulf Coast, which is especially vulnerable due to a combination of sea level rise, storm surges, erosion, and land subsidence. In 2011, the U.S. had net imports of 45% of oil consumed and 56% of the imports passed through Gulf Coast ports (EIA 2012).

More frequent disruptions and damage to roads, tracks, runways, and navigation channels are projected in coastal areas beyond the Gulf Coast. Thirteen of the nation's largest airports have at least one runway with an elevation within 12 feet of current sea levels (Airnav LLC 2012). Most ocean-going ports are in low-lying coastal areas, including two of the most important for imports and exports: Los Angeles/Long Beach and Galveston/Houston. Many federally maintained navigation channels have deteriorated in recent years to dimensions less than those authorized, which has resulted in reduced levels of service that affect navigation safety and reliability (U.S. Army Research and Development Center 2009). Extreme floods and storms associated with climate change will lead to increased movement of sediment and build up of sandy formations in channels. Channels that are not well maintained and have less sedimentation storage volume will thus be more vulnerable to significant, abrupt losses in navigation service levels. Additional channel storage capacity that may be created by sea level rise will also increase water depths and increase sedimentation in channels. See Ch. 25: Coastal Zone Development and Ecosystems for additional discussion of coastal transportation impacts.

Airport Runways Near Sea Level


**Figure 5.2:** Airport Runways Near Sea Level

**Caption:** Thirteen of the largest airports in the U.S. have at least one runway with an elevation within 12 feet of current sea level (Reference: www.airnav.com/airports). Sea level rise will pose a threat to low-lying infrastructure such as these. The inset is U.S. Geological Survey data of San Francisco Bay showing areas (in blue) which are susceptible to 16 inches of sea level rise by 2050 (San Francisco Bay Conservation and Development Commission), which is within the range projected for global sea level rise in Ch. 2: Our Changing Climate.

### *Weather Disruptions*

**Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.**

Changes in precipitation patterns, particularly more intense storms and drought, will affect transportation systems across the country. Severe storm delays disrupt almost all types of transportation. Storm drainage systems for highways, tunnels, airports, and city streets could prove inadequate, resulting in localized flooding. Bridge piers are subject to scour as runoff increases stream and river flows, potentially weakening bridge foundations. Severe storms will disrupt highway traffic leading to more accidents and delays. More airline traffic will be delayed or canceled.

Inland waterways may well experience greater floods, with high flow velocities that are unsafe for navigation and shut channels down intermittently. Numerous studies indicate that there is increasing severity and frequency of flooding throughout much of the Mississippi and Missouri River Basins (Black 2008; Criss and Schock 2001). In the Upper Mississippi/Missouri Rivers, there have been two 300- to 500-year floods over the past 20 years (Holmes et al. 2008). Drought increases the probability of wildfires, which affect visibility severely enough to close roads and airports. Drought can lower vessel drafts on navigable rivers and associated lock and dam pools. Less ice formation on navigable waterways has the potential to increase seasonal windows for passage of navigation.

Hurricanes in the Atlantic are expected to increase in intensity and frequency (see Ch. 2: Our Changing Climate, Key Message 8). As hurricanes approach landfall, they create storm surge, which may carry water far inland. The resulting flooding, wind damage, and bridge destruction disrupts virtually all transportation systems in the affected area.

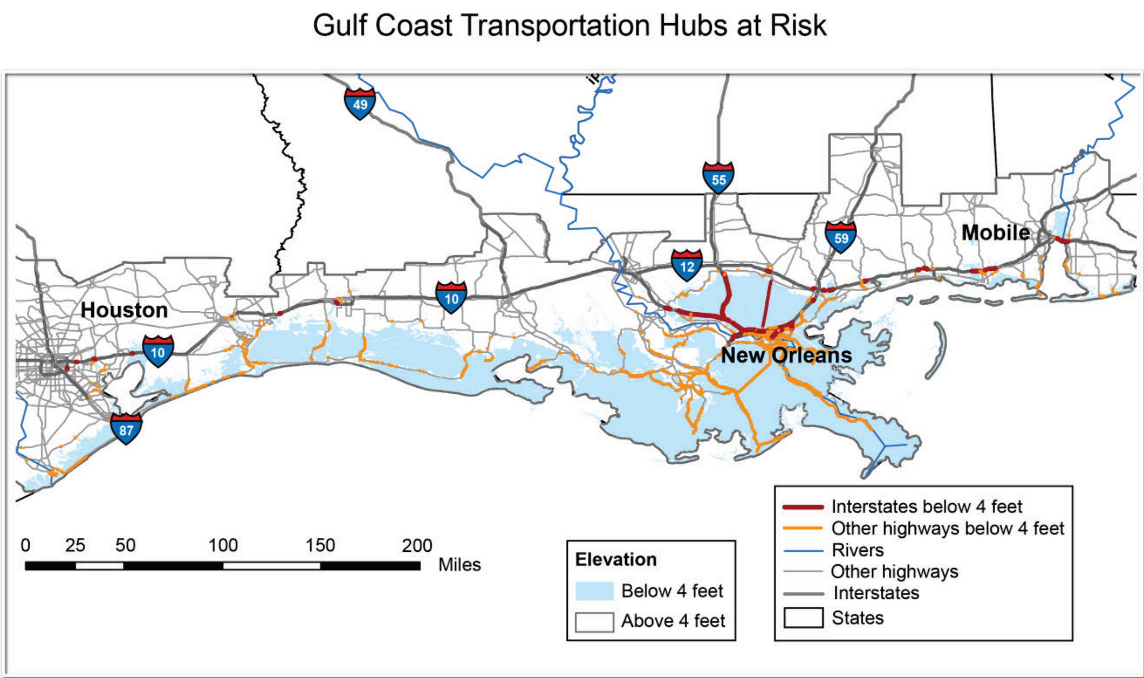


**Figure 5.3:** Gulf Coast Transportation Hubs at Risk

**Caption:** Within this century, 2,400 miles of major roadway are projected to be inundated by sea level rise in the Gulf Coast region. The map shows roadways at risk in the event of a sea level rise of about 4 feet, which is within the range of projections for this region in this century (see also Ch. 2: Our Changing Climate, Key Message 9). In total, 24% of interstate highway miles and 28% of secondary road miles in the Gulf Coast region are at elevations below 4 feet. Source: 2009 NCA/CCSP SAP 4.7

**Box 2: Hurricane Sandy**

On October 29, 2012, Hurricane Sandy dealt the transportation systems of New Jersey and New York and environs a massive blow, much in line with vulnerability assessments conducted over the past four years (Jacob et al. 2008; New York State 2011; New York State Sea Level Rise Task Force 2010; Zimmerman and Faris 2010). All tunnels and most bridges leading into New York City were closed during the storm. A nearly fourteen-foot storm surge (The New York Times 2012) flooded the Queens Midtown, Holland, and Carey (Brooklyn Battery) tunnels, which remained closed for at least one week (two weeks for the Carey Tunnel) while floodwaters were being pumped out and power restored. The three major airports, Kennedy, Newark, and LaGuardia, flooded, with LaGuardia absorbing the worst impact and closing for three days (The Port Authority of New York & New Jersey 2012a). Almost 7.5 million passengers per day ride the New York City subways and buses (Metropolitan Transportation Authority 2012a). Much of the New York City subway system below 34th Street was flooded, including all seven tunnels under the East River to Brooklyn and Queens. In addition to removing the floodwaters, all electrical signaling and power systems (the third rails) had to be cleaned, inspected, and repaired. Service on most Lower Manhattan subways was suspended for at least one week (Vantuono

2012), as was the PATH system to New Jersey (The Port Authority of New York & New Jersey 2012b). Commuter rail service with over 500,000 passengers per day (Metropolitan Transportation Authority 2012a) to New Jersey, Long Island, and northern suburbs was similarly affected for days or weeks with flooded tunnels, downed trees and large debris on tracks, and loss of electrical power (Metropolitan Transportation Authority 2012b). All of this disruption was in addition to the miles of local roads, streets, underpasses, parking garages, and bridges flooded and/or badly damaged in the region, and countless parked vehicles that sustained water damage. Flooded roadways prevented the New York Fire Department from responding to a fire that destroyed over 100 homes in the Breezy Point neighborhood of Brooklyn (Hampson 2012).

Hurricane Sandy's storm surge produced nearly four feet of floodwaters throughout the Port of New York and New Jersey, damaging electrical systems, highways and rail track, and port cargo, displacing hundreds of shipping containers, and causing ships to run aground (The Port Authority of New York & New Jersey 2012c). Floating debris, wrecks, and obstructions in the channel had to be cleared before the Port was able to reopen to incoming vessels within a week (U.S. Army Corps of Egineers 2012, personal communication). Pleasure boats were damaged at marinas throughout the region. On a positive note, the vulnerability analyses prepared by the metropolitan New York authorities and referenced above provided a framework for efforts to control the damage and restore service more rapidly. Noteworthy are the efforts of the Metropolitan Transit Authority to protect vital electrical systems and restore subway service to much of New York within four days.

The impacts of this extraordinary storm on one of the nation's most important transportation nodes were felt across the country. Airline schedules throughout the U.S. and internationally were snarled; Amtrak rail service along the East Coast and as far away as Buffalo and Montreal was curtailed; and freight shipments in and out of the hurricane impact zone were delayed. The resultant direct costs to the community and indirect costs to the economy will undoubtedly rise into the tens of billions of dollars. While the storm cannot be tied directly to climate change, given that tropical storms have hit the northeast before as late as December (Burt 2012), it is nevertheless indicative of what powerful tropical storms and higher sea levels could bring on a more frequent basis in the future.

Hurricane Sandy Causes Flooding in New York City Subway Stations


**Figure 5.4:** Hurricane Sandy Causes Flooding in New York City Subway Stations

**Caption:** The nation's busiest subway system sustained the worst damage in its 108 years of operation on October 29, 2012, as a result of Hurricane Sandy. Millions of people were left without service for at least one week after the storm, as the Metropolitan Transportation Authority rapidly worked to repair extensive flood damage (Vantuono 2012).

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**Risks and Consequences**

Risk is a function of both likelihood of impact and the consequences of that impact. Table 1 is an illustrative application of a risk matrix adapted from the Port Authority of New York and New Jersey. As shown, different types of climate-related incidents/events can have associated with them a likelihood of occurrence and a magnitude of the consequences if the incident does occur.

In assessing consequences, the intensity of system use, as well as the existence or lack of alternative routes, must be taken into account. Disabling a transportation facility can have ripple effects across a network, with trunk lines and hubs having the most widespread impacts (McLaughlin et al. 2011).

**Table 5.1: Illustrative Risks of Climate-related Impacts**

| | | Likelihood of Occurrence | | | |
|---|---|---|---|---|---|
| | | **Low** | **Medium** | **High** | **Virtually Certain** |
| Magnitude of Consequences | **High** | Subway and tunnel flooding | Increased widespread flooding of transportation facilities | Major localized flooding disrupts transportation systems | Inundation of coastal assets due to storm surge |
| | **Medium** | Increased rock/mud slides blocking road and rail facilities | Train derailment due to rail buckling | Increased disruption of barge traffic due to flooding | Short-term road flooding and blocked culverts due to extreme events |
| | **Low** | Lower visibility from wildfires due to drought conditions | Northward shift of agricultural production places more demand and stress on roads and systems not prepared for higher volumes | Pavement heaving and reduced pavement life due to high temperatures | Inundation of local roads due to sea level rise |
| | **Positive (beneficial)** | Reduced flight cancellations due to fewer blizzards | Reduced maintenance costs for highways and airports due to warmer winters | Reduced Great Lakes Freezing, leading to longer shipping season | Longer seasonal opening of Northwest Passage |

**Note:** Table 1 relates to overall national expectations. This kind of matrix is likely to be most valuable and accurate if used at the state/regional/local levels.

(Source: Adapted from McLaughlin et al. 2011).

Assessing the consequences of climate change should encompass the broad array of factors that influence the nation's transportation system, and should consider changes in population, society, technology, prices, regulation, and the economy that eventually affect transportation system performance (Jaroszweski et al. 2010). For example, the trend in recent years in the U.S. economy of adopting just-in-time logistics increases the vulnerability of businesses to day-to-day disruptions caused by weather and flooding.

## *Costs and Adaptation Options*

**Climate change impacts will increase costs to transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.**

Adaptation strategies can be employed to reduce the impact of climate change related events and the resulting consequences. Consideration of adaptation strategies in the transportation sector is especially important in the following five areas:

- **Transportation and land-use planning:** deciding what infrastructure to build and where to build it, as well as planning for vulnerable areas of the community and impacts on specific population groups.
- **Vulnerability and risk assessment**: identifying existing vulnerable facilities and systems, together with the expected consequences.
- **New infrastructure design**: adapting new infrastructure designs that anticipate changing environmental and operational conditions.
- **Asset management**: adapting existing infrastructure and operations that respond to current and anticipated conditions, including changed maintenance practices and retrofits.
- **Emergency response:** anticipating expected disruptions from extreme weather events, and developing emergency response capability.

Role of Adaptive Strategies in Reducing Impacts and Consequences

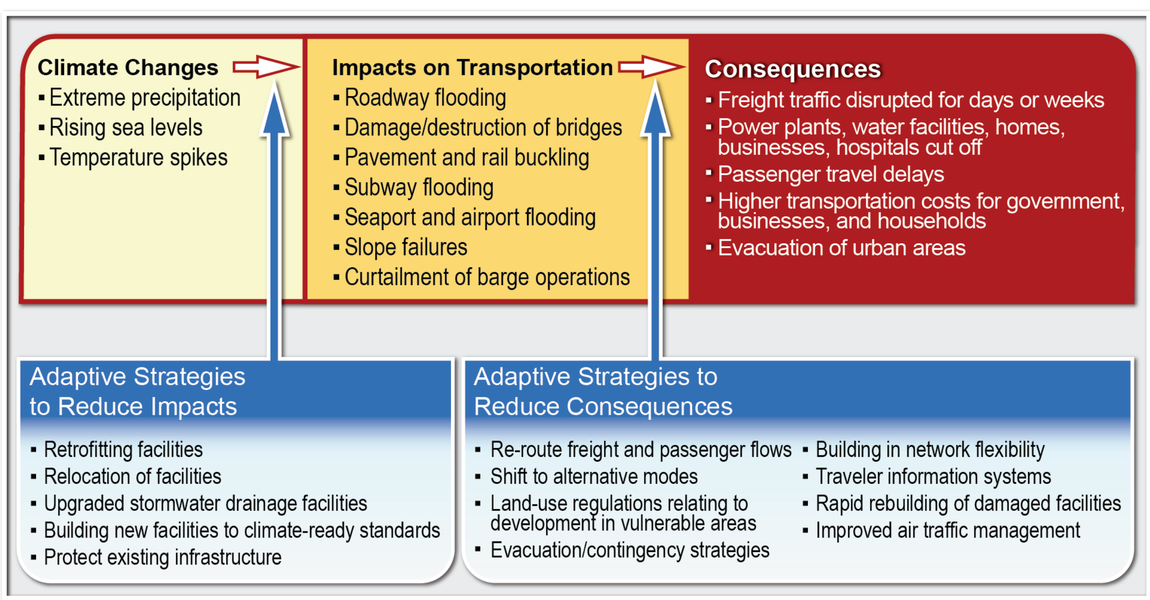


**Figure 5.5:** Role of Adaptive Strategies in Reducing Impacts and Consequences

**Caption:** Many projected climate change impacts and resulting consequences on transportation systems can be reduced through a combination of infrastructure modifications, improved information systems, and policy changes.

Adaptation takes place at multiple levels, from individual households and private businesses to federal, state, and local governments. The impacts associated with climate change are not new, since flooding, storm surge, and extreme heat have long been challenges. What is new is the changing frequency, intensity, and location/geography of impacts and hazards.

Responding effectively to present and future environmental challenges enhances the resilience of communities. Examples include improvements in storm water management, coastal zone management, and coastal evacuation plans.

At the national level, the transportation network has some capability to adjust to climate-related disruptions due to the presence of network redundancy – multiple routes are often possible for long-distance travel, and more than one mode of transportation may be used for travel. However, in some cases, only one major route connects major destinations, such as Interstate 5 between Seattle and San Francisco; movements along such links are particularly vulnerable to disruption.

**Box 3: Winter Storm-Related Closures of I-5 and I-90 in Washington State, 2007–08**
In December, 2007 heavy rainfall west of I-5, combined with melting snow from the mountains, created extremely high floodwaters in western Washington State. Six-hour rainfall amounts were near a 100-year event for areas in Southwest Washington. High winds, heavy rains, mudslides, and falling trees made travel unsafe on highways. Downed power lines blocked roads, and, in many urban areas, rainwater overwhelmed drainage systems and flooded roadways.

The combined economic impact in the I-5 and I-90 corridors was estimated at almost $75 million, of which some $47 million was associated with the I-5 disruption and $28 million with the I-90 corridor. Estimated highway damage from the winter storm was $18 million for state routes and another $39 million for city and county roads (WSDOT 2008).

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Disruptions to the nation's inland water system from floods or droughts can, and has, totally disrupted barge traffic. Severe droughts throughout the upper Midwest in 2012 reduced flows in the Missouri and Mississippi Rivers to near record levels, impacting barge traffic. Further flow decreases occasioned by reductions in discharges from the upper Missouri River dams are projected to close the rivers to barge traffic above St Louis by year-end 2012 (The Associated Press 2012). While alternative modes, such as rail and truck, may alleviate some of these disruptions, it is impractical to shift major product shipments such as Midwest grain to other modes of transportation – at least in the near term (Rypinski 2011). While extreme weather events will continue to cause flight cancellations and delays, many weather delays from non-extreme events are compounded by inadequacies in the current national air traffic management system (Oster and Strong 2008). Improvements in the air traffic system, such as those anticipated in the FAA's NextGEN (www.faa.gov/nextgen/), should reduce weather-related delays.

At the state and local level, there is less resilience to be gained by alternative routing, and impacts may be more intense. For example, significant local and regional disruption and economic costs could result from the flooding of assets as diverse as New York's subways, Iowa's roads, San Francisco's airports, and Vermont's bridges.

Climate change is one of many factors, and an increasingly important one, that must be addressed by state, regional, and local agencies as they plan for new and rehabilitated facilities. By incorporating climate change routinely into the planning process, governments can reduce the vulnerability to climate change impacts and take actions that enhance the resilience of the transportation system to adverse weather conditions. Indeed, governments at various levels are taking action as described below.

Land-use planning can reduce risk by avoiding new development in flood-prone areas; conserving open space to enhance drainage; and relocating or abandoning structures or roads that have experienced repeated flooding. The National Flood Insurance Program encourages buyouts of repetitive loss structures and preservation of open space by reducing flood insurance rates for communities that adopt these practices.

An important step in devising an adaptation plan is to assess vulnerabilities. The Federal Highway Administration funded pilot projects in five coastal states to test a conceptual framework for evaluating risk (DOT 2005). The framework identifies transportation assets, evaluates the likelihood of impact on specific assets, and assesses the seriousness of such impacts.

Several state and local governments have conducted additional vulnerability assessments that identify potential impacts to transportation systems, especially in coastal areas. Detailed work has been undertaken by New York City (Jacob et al. 2008; New York State Sea Level Rise Task Force 2010; Rosenzweig et al. 2011b; Zimmerman and Faris 2010), California (California Natural Resources Agency 2009), Massachusetts (Massachusetts Energy and Environmental Affairs 2011), Washington (Washington State University 2012), Florida, and Boston (City of Boston 2011).

**Box 4: Planning for Climate Change**
The Metropolitan Planning Organization in Charlotte County-Punta Gorda, Florida conducted long-range scenario planning that integrated climate change (CCMPO 2010). A "smart growth" scenario that concentrated growth in urban centers was compared with a "resilient growth" scenario that steered development away from areas vulnerable to sea level rise. Planners evaluated the scenarios based on projected transportation performance outcomes and selected a preferred scenario reflecting aspects of each alternative. Charlotte County exemplifies how local governments can incorporate aspects of climate change into transportation planning.

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Non-coastal states and regions have also begun to produce vulnerability assessments. Midwestern states including Wisconsin (WICCI 2011), Iowa (Iowa Climate Change Impacts Committee 2011), and Michigan (Michigan Department of Transportation 2012) have addressed increasing risk of flooded roadways and other impacts.

Transit systems are already implementing measures that reduce vulnerability to climate impacts, including rail buckling. Portland’s transit agency has been installing expansion joints at vulnerable locations, improving reliability of rail service (Hodges 2011). In New York, ventilation grates are being elevated to reduce the risk of flooding (Jacob et al. 2008).

Transportation agencies are incorporating climate change into ongoing design activities. For example, the Alaska Department of Transportation spends more than $10 million annually on shoreline protection, relocations, and permafrost protection for roadways (see “Thawing Alaska” above) (Adaptation Advisory Committee 2010). In May 2011, the California Department of Transportation (Caltrans) issued guidance to their staff on whether and how to incorporate sea level rise into new project designs (Caltrans 2011).

States have begun to integrate climate impacts into Transportation Asset Management, a systematic process for monitoring the conditions of roads and transit facilities (Meyer et al. 2010; Radow and Neudorff 2011). Maryland is working to prioritize assets taking sea level rise and increased storm intensity into account, and is developing a tool to track assets and assess vulnerability (Slater 2011). Florida DOT continually monitors conditions on roads and bridges, and is developing a statewide inventory and action plan for high-risk bridges (Jacobs 2009). Among inland states, Michigan DOT has identified a wide range of operational and asset management changes to adjust to climate change (Michigan Department of Transportation 2012).

The risk of flooding for transportation infrastructure can be reduced by effective stormwater and stream/river management. Following Tropical Storm Irene, Vermont state agencies are working on stream and river management to reduce conditions that exacerbate flooding impacts on transportation (Tetreault 2011, Interview).

**Box 5: Tropical Storm Irene Devastates Vermont Transportation in August 2011**

In August of 2011, Vermont was inundated with rain and massive flooding from Tropical Storm Irene, closing down 146 segments of the state road system along with more than 200 bridges, at an estimated cost of up to $175 to $200 million for rebuilding state highways and bridges. An additional 2,000 or more municipal roads and nearly 1,000 culverts were damaged, and more than 200 miles of state-owned rail required repair (VANR 2012).

The volume of water was unprecedented, as was the power of the water in the rivers running through the state. Culverts and bridges were affected and slope stability was threatened as a result of the immense amount and power of water and subsequent flooding.

When asked about the lessons learned, VTrans indicated the importance of good maintenance of riverbeds as well as roads. VTrans is working with the Vermont Agency of Natural Resources, looking upstream and downstream at the structure of the rivers, recognizing that risk reduction may involve managing rivers as much as changing bridges or roadways.

Rich Tetreault of VTrans emphasized that “Certainly we will be looking to right-size the bridges and culverts that need to be replaced … Knowing that we do not have the funds to begin wholesale rebuilding of the entire highway network to withstand future flooding, we will also enhance our ability to respond” when future flooding occurs (Tetreault 2011, Interview).

Tropical Storm Impact on Vermont Road

**Figure 5.6:** Tropical Storm Impact on Vermont Road

**Caption:** Vermont Route 131, outside Cavendish, a week after Tropical Storm Irene unleashed severe precipitation and flooding that damaged many Vermont roads, bridges, and rail lines. Photo courtesy of Vermont Agency of Transportation.

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Effective asset management requires significant data and monitoring of transportation assets. Improved weather and road-condition information systems enable transportation system managers to anticipate and detect problems better and faster – enabling them to close systems if needed, alert motorists, and dispatch maintenance and snow-removal crews. As Michigan DOT has noted, the increasing changes in snowstorms means that existing models used for snow and ice removal procedures are no longer reliable, requiring better monitoring and new models, as well as better roadway condition detection systems (Michigan Department of Transportation 2012).

Similarly, regular maintenance and cleaning of urban levee and culvert systems reduces the risk of roads and rails being inundated by flooding.

Extreme weather, such as hurricanes or intense storms, stresses transportation at precisely the time when smooth operation is critical. Effective evacuation planning, including early warning systems, coordination across jurisdictional boundaries, and creating multiple evacuation routes builds preparedness. Identifying areas with high concentrations of vulnerable and special-needs populations (including elderly, disabled, and transit-dependent groups) enhances readiness, as does identifying assets such as school buses that can be deployed for households that do not own vehicles.

# Traceable Accounts

## Chapter 5: Transportation

**Key Message Process:** In developing key messages, the chapter author team engaged, via teleconference, in multiple technical discussions from January through May 2012 as they reviewed numerous peer reviewed publications. The author teams review included a foundational Technical Input Report for the National Climate Assessment, "Climate Impacts and U.S. Transportation (DOT 2012)", and approximately 20 additional technical inputs to the NCA. Other published literature and professional judgment were also considered as the chapter key messages were developed. The chapter author team met in St. Louis, MO in April 2012 for expert deliberation and finalization of key messages.

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| **Key message #1/4** | **The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are reducing the reliability and capacity of the U.S. transportation system in many ways.** |
| **Description of evidence base** | Climate impacts in the form of sea level rise, changing frequency of extreme weather events, heat waves, precipitation changes, Arctic warming, and other climatic conditions are documented in Ch. 2: Our Changing Climate of this report.<br><br>Climate can be described as the frequency distribution of weather over time. The authors believe that climate change will affect the reliability and capacity of U.S. transportations systems because existing weather conditions, flooding and storm surge demonstrably affect U.S. transportation systems, and that, consequently, changes in the frequency of these conditions will inevitably affect transportation systems. This view is supported by multiple studies of the impacts of weather and climate change on particular transportation systems or particular regions.<br><br>An aggregate summary of impacts of climate change on U.S. transportation can be found in (NRC 2008). A paper commissioned for this effort considers specific impacts of various forms of climate change on infrastructure: (Meyer 2008). The effects of climate on transit systems are summarized in (Hodges 2011). The impact of heat and other climate effects on rail systems are described by (Rossetti and Johnsen 2011).<br><br>Future impacts of sea level rise and other climatic effects on transportation systems in the Gulf Coast were examined by (CCSP 2008) The impacts of climate change on New York State, including transportation system were undertaken by (Rosenzweig et al. 2011b).<br><br>Weather impacts on road systems are discussed in (DOT 2012) and numerous other sources. Weather impacts on aviation operations are discussed in (Kulesa 2003) and numerous other sources.<br><br>In addition, the key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation (DOT 2012)". Technical Input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.<br><br>Additional peer-reviewed publications discuss that Arctic warming is affecting existing Alaskan transportation infrastructure today, and is projected to allow the seasonal opening of the Northwest Passage to freight shipment (Arctic Council 2009) . |

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| **New information and remaining uncertainties** | Recent changes in global sea level rise estimates documented in Ch.2: Our Changing Climate, Key Message 9 of this report have not been incorporated into existing regional studies of coastal areas. In addition, recent research by USGS on the interaction between seal level rise, wave action, and local geology have been incorporated in only a few studies (Gutierrez 2011).<br><br>Specific estimate of climate change impacts on transportation are acutely sensitive to regional projections of climate change, and, in particular, to the scale, timing, and type of predicted precipitation. New (CMIP5-based) regional climate projections will therefore affect most existing specific estimates of climate change impacts on transportation. Transportation planning in the face of uncertainties about regional-scale climate impacts present particular challenges.<br><br>Impacts of climate on transportation system operations, including safety and congestion, both on road systems and in aviation, have been little studied to date.<br><br>The future evolution of society and the transportation systems that serve society is itself uncertain, making the evaluation of impacts on an uncertain future system itself uncertain.<br><br>Adaptation can significantly ameliorate impacts on the transportation sector, however, evaluation of adaptation costs and strategies for the transportation sector is at a relatively early stage. |
| **Assessment of confidence based on evidence** | Given the evidence described above, the authors are highly confident that climate change will affect transportation systems. Confidence is high, given current climate projections, particularly sea level rise and extreme weather events, that transportation systems will be affected by climate change. |

| **CONFIDENCE LEVEL** | | | |
|---|---|---|---|
| **Very High** | **High** | **Medium** | **Low** |
| Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus | Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus | Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought | Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts |

# Chapter 5: Transportation

**Key Message Process:** See key message #1.

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| **Key message #2/4** | **Sea level rise coupled with storm surge will continue to increase the risk of major coastal impacts, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.** |
| **Description of evidence base** | Estimates of sea level rise are documented in Ch. 2: Our Changing Climate, Key Message 9 of this report.<br><br>The prospective impact of sea level rise and storm surge on transportation systems is illustrated by the impact of recent hurricanes on U.S. coastlines. In addition, research on impacts of sea level rise and storm surge on transportation assets in particular regions of the United States demonstrate the potential for major coastal impacts (CCSP 2008; Rosenzweig et al. 2011b) (Suarez et al. 2005), and numerous other reports. Note that most existing literature on storm surge and sea level rise impacts on transportation systems is based on a global sea level rise of less than one meter (about 3 feet).<br><br>In addition, the key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation (DOT 2012). Technical Input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. |
| **New information and remaining uncertainties** | As noted above, new estimates of sea level rise have overtaken most of the existing literature on transportation and sea level rise in the United States. In addition, it is not clear that the existing literature reflects recent USGS work on interactions between sea level rise, wave action, and local geology (Gutierrez 2011).<br><br>New global sea level rise estimates will require development of new regional sea level rise estimates, as well as revision of erosion modeling, since transportation and other infrastructure impacts must necessarily be studied in a local context.<br><br>Generally speaking, modeling of sea level rise impacts using existing USGS NED data has well-understood limitations. Since NED data is freely and easily available, it is often used for preliminary modeling. More accurate and more recent elevation data may be captured via LIDAR campaigns, and this data collection effort will be necessary for accurate understanding of regional and local sea level rise and storm surge impacts (See CCSP 2009b).<br><br>Accurate understanding of transportation impacts is specific to particular infrastructure elements, so detailed inventories of local and regional infrastructure must be combined with detailed and accurate elevation data and the best available predictions of local sea level rise and storm surge. Therefore, national assessments of sea level rise must be built on detailed local and regional assessments.<br><br>Improved modeling is needed on the interaction between sea level rise, storm surge, tidal movement and wave action to get a better understanding of the dynamics of the phenomenon. |
| **Assessment of confidence based on evidence** | The authors have high confidence that sea levels are rising and that storm surge on top of these higher sea levels pose risks to coastal transportation, based |

| CONFIDENCE LEVEL | | | |
|---|---|---|---|
| **Very High** | **High** | **Medium** | **Low** |
| Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus | Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus | Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought | Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts |

# Chapter 5: Transportation

**Key Message Process:** See key message #1.

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| **Key message #3/4** | **Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.** |
| **Description of evidence base** | The key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation (DOT 2012)". Technical Input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.<br><br>Specific regional climate impacts can be identified in each NCA region of the country. Specific climate impacts on transportation by region include:<br><br>In Alaska, rising temperatures cause permafrost to melt, causing damage to roadbeds, airfields, pipelines, and other transportation infrastructure (Adaptation Advisory Committee 2010)<br><br>In the Northeast, the Chesapeake region is likely to experience particularly severe local sea level rise due to geologic subsidence (CCSP 2009b), and increased precipitation generally (see Ch. 2: Our Changing Climate, Key Message 5, and Ch.16: Northeast), along with an increased incidence of extreme weather events. The presence of large populations with associated transportation system in coastal areas increased the potential impacts of sea level rise, storm surge, and precipitation-induced flooding.<br><br>The Southeast includes Virginia, so it shares the threat of regional sea level rise in the Chesapeake, as well as significant threat to transportation infrastructure of national significance in Louisiana (CCSP 2008), as well as the interacting effects of sea level rise and increased precipitation, and extreme events.<br><br>Midwest transportation infrastructure is subject to changing water levels on the Great Lakes (Angel and Kunkel 2010) and barge traffic disruptions due to flooding or drought on the Mississippi/Missouri/Ohio river system, as might be induced by changes in precipitation patterns.<br><br>In the Southwest, rail and highway systems may be exposed to increased heat damage from the higher temperatures. The key risk is that declining precipitation (see Ch. 2: Our Changing Climate, Key Message 5) may induce changes in the economy and society of the Southwest that will affect the transportation systems that serve this region. San Francisco Bay, which encompasses two major airports and numerous key transportation links, is at risk for sea level rise and storm surge (California Natural Resources Agency 2009).<br><br>Much of the economy of the Northwest is built around electricity and irrigation from a network of dams. The performance of this system may be affected by changing precipitation patterns, with potential consequences for agriculture and industry, and, consequently for transportation systems. In addition, the Seattle area may be affected by sea level rise (Washington State University 2012)<br><br>Many relevant and recent climate data and models predict more intense precipitation events in much of the U. S. especially the Great Plains, Midwest, Northeast, and Southeast with decreased precipitation in parts of the Southwest and Southeast (see Ch. 2: Our Changing Climate, Key Message 5). |
| **New information and** | New regional climate model data from CMIP5 will have a significant impact on |

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| **remaining uncertainties** | regional impact assessments.<br><br>Climate data desired by transportation planners may be different than the projections generated by regional climate models. This presents a number of challenges:<br><br>Regional scale transportation impacts are often determined by flood risk and by water flows on rivers and streams. Flooding is, of course, linked to precipitation, but the linkage between precipitation and hydrology is very complex. Precipitation, as represented in climate models, is often difficult to reduce to predictions of future flooding, which is what infrastructure designers would like to have.<br><br>Similarly, an ice storm would be an extreme event for a transportation planner, but the frequency of ice storms probably cannot be derived from climate models. More generally, improved methods of deriving the frequency infrastructure-affecting weather events from regional climate models may be helpful in assessing climate impacts on transportation systems.<br><br>Recent data clearly show and climate models further substantiate an increase in the intensity of precipitation events throughout much of the U.S.<br><br>There is a need for a better definition of the magnitude of increased storm intensity so that accurate return frequency curves can be established.<br><br>There are uncertainties associated with the correlation between a warming climate and increased hurricane intensity.<br><br>In regions likely to see decreased precipitation, especially those areas subject to drought, stronger correlations to fire threat and lowered water levels in major waterways are needed. |
| **Assessment of confidence based on evidence** | Given the evidence base and remaining uncertainties, confidence is high that extreme weather events will affect transportation in all areas of the country. |

| **CONFIDENCE LEVEL** | | | |
|---|---|---|---|
| **Very High** | **High** | **Medium** | **Low** |
| Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus | Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus | Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought | Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts |

1 # Chapter 5: Transportation

2 **Key Message Process:** See key message #1.

| **Key message #4/4** | **Climate change impacts will increase costs to transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.** |
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| **Description of evidence base** | The economic cost of climate change to the transportation sector has been little studied. However, there is substantial evidence that costs will be significant A recent study of climate change in New York indicated that a storm surge severe enough to flood Manhattan tunnels might cost as much as $100 billion (Rosenzweig et al. 2011b) A study of the risk to specific infrastructure elements in Alaska (Larsen 2007) a estimated the net present value of the extra cost from climate change at $2-$4 billion through 2030, and $4-$8 billion through 2080.<br><br>The indirect evidence for significant costs from climate change impacts begin with the consequences of recent hurricanes, particularly on the Eastern Seaboard, where Hurricane Irene, a rather minor storm, produced unexpectedly heavy infrastructure damage from heavy rains. The economic cost of infrastructure damage is often greater than the cost of repairing or replacing infrastructure. For example, when the I-35W bridge collapsed in 2007, the State of Minnesota estimated the economic cost of lost use at $0.4 million per day, while the replacement cost of the bridge was $234 million (Haugen 2008; Xie and Levinson 2011)<br><br>In addition a recent study of on-road congestion estimates the annual cost of highway congestion at about $100 billion (Schrank et al. 2011) the Federal Highway Administration estimates that weather accounts for about 15 percent of total delay (Cambridge Systematics and Texas Transportation Institute 2005). Similarly, a recent study of aviation congestion indicates that the annual cost of airline delay is about $33 billion (Ball et al. 2010) and that weather accounts for more than a third of airline delays. There is a strong circumstantial case to be made that increased frequency of extreme events (as defined by climate scientists) will produce increase traffic and aviation delays. Given the scale of current costs, even small changes in delay can have substantial economic costs.<br><br>There is little published material on transportation adaption costs and benefits in the literature, in part because “adaptation” is an abstraction. Climate change is statistical weather, and manifests itself as a change in the frequency of events that would still occur (but with lower frequency) in the absence of climate change. Transportation agencies decide to protect (or not) specific pieces of infrastructure based on a range of considerations, including age and condition, extent of current and future usage, and cost of protection, as well as changing weather patterns. The authors, however, are aware, that transportation systems have always been required to adapt to changing conditions, and that, in general, it is almost always far less expensive to protect useful infrastructure than to wait for it to collapse. This professional experience, based on examination of multitudes of individual engineering studies, is the basis for the conclusion in the report,<br><br>There are numerous examples of actions taken by state and local governments to enhance resilience and reduce climate impact costs on transportation including land-use planning to discourage development in vulnerable areas, establishment of design guidelines to reduce vulnerability to sea level rise, use of effective stormwater management techniques and coordinated emergency response systems. |
| **New information and** | There is relatively little information on the costs of climate change in the transportation sector, and less on the benefits of adaptation. Much of the available |

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| **remaining uncertainties** | research is focused on costs of replacing particular assets, with far less effort devoted to impacts of climate change on transportation systems.<br><br>Calculating climate impact and adaptation costs and benefits is an exceptionally complex problem, particularly at high levels of aggregation, since both costs and benefits accrue based on a multitude of location specific events. In addition, all of the methodological issues that are confronted by any long-term forecasting exercise are present. The problem may be more manageable at the local and regional scales at which most transportation decisions are usually made. |
| **Assessment of confidence based on evidence** | The authors have high confidence that climate impacts will be costly to the transportation sector, but are far less confident in assessing the exact magnitude of costs, based on the available evidence and their experience. The authors also have high confidence, based upon their experience, that costs may be significantly reduced by adaptation action, though, as noted the magnitude of such potential reductions on a national scale would be difficult to determine. |

| **CONFIDENCE LEVEL** | | | |
|---|---|---|---|
| **Very High** | **High** | **Medium** | **Low** |
| Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus | Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus | Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought | Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts |

**References**

Adaptation Advisory Committee, 2010: Alaska's Climate Change Strategy: Addressing Impacts in Alaska. A. C. C. Sub-Cabinet, Ed.

Airnav LLC, cited 2012: Airport Information. [Available online at www.airnav.com/airports]

Angel, J. and K. Kunkel, 2010: The Response of Great Lakes Water Levels to Future Climate Scenarios. *Journal of Great Lakes Research*, **36,** 55

Arctic Council, 2009: Arctic Marine Shipping Assessment Report 2009. *Tromsø, Norway: Arctic Council*

Ball, M., C. Barnhart, M. Dresner, M. Hansen, K. Neels, A. Odoni, E. Peterson, L. Sherry, A.A. Trani, and B. Zou, 2010: Total delay impact study: a comprehensive assessment of the costs and impacts of flight delay in the United States

Black, H., 2008: Unnatural Disaster: Human Factors in the Mississippi Floods. *Environmental Health Perspectives*, **116,** A390-393

Burt, C.C., 2012: Late Season Tropical Storms that have affected the U.S. north of the Hatteras. *Wunderground.com*.

California Natural Resources Agency, 2009: The California Climate Adaptation Strategy 2009: A Report to the Governor of the State of California. N. R. Agency, Ed.

Caltrans, 2011: Guidance of Incorporating Sea-Level Rise: For Use in the Planning and Development of Project Initiation Documents.State government guidance report. California Department of Transportation, Ed.

Cambridge Systematics and Texas Transportation Institute, 2005: Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation

CCMPO, 2010: Charlotte County-Punta Gorda Long Range Transportation Plan 2035: Summary Report. MPO report. Charlotte County-Punta Gorda Metropolitan Planning Organization, Ed.

CCSP, 2008: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Study, Phase I

——, 2009b: Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. J. Titus, E. K. Anderson, D. R. Cahoon, S. Gill, R. E. Thieler, and J. S. Williams, Eds., US EPA/CCSP

City of Boston, cited 2011: A Climate of Progress: City of Boston Climate Action Plan Update 2011. [Available online at http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf]

Criss, R.E. and E.L. Schock, 2001: Flood Enhancement Through Flood Control. *Geoloogy*, **29,** 875-878

DOT, 2005: Congestion and Reliability: Trends and Advanced Strategies for Congestion Management.

——, 2012: Climate Variability and Change in Mobile, Alabama: Task 2 Final Report. Developed under Phase 2 of Impacts of Climate Change and Variability on Transportation Systems and Infrastructure (Gulf Coast Study). Report # FHWA-HEP-12-053. [Available online at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/index.cfm .]

——, 2012: Climate Impacts and Transportation: Technical Input Report for the National Climate Assessment. DOT OST/P-33 (Draft, February 2012).

EIA, 2011: Annual Energy Review 2011. statistical report http://www.eia.gov/totalenergy/data/annual/

——, 2012: Petroleum and Other Liquids. [Available online at http://www.eia.gov/petroleum/data.cfm]

EPA, 2011: Inventory of U.S. Greenhouse Gas Emissions & Sinks, 2000-2009. statistical report http://www.epa.gov/climatechange/emissions/usinventoryreport.html

Gutierrez, B.T., 2011: A Bayesian Network to Predict Coastal Vulnerability to Sea Level Rise. *Jounral of Geophyisical Research*, **116** doi: 10.1029/2010JF001891

Hampson, R., 2012: Hurricane Sandy couldn't kill the spirit of New York's seaside haven. *USA Today*.

Haugen, D., 2008: Officials Hail new I-35 Bridge and the Workers Wh Make it Happen. *Minneapolis Post*.

Hodges, T., 2011: Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation, 75 pp

Holmes, R.R.J., T.A. Koenig, and K.A. Karstensen, 2008: Flooding in the United States Midwest. USGS Professional Paper 1775

Iowa Climate Change Impacts Committee, 2011: Climate Change Impacts on Iowa 2010

Jacob, K., C. Rosenzweig, R. Horton, D. Major, and V. Gornitz, 2008: MTA Adaptations to Climate Change: A Categorical Imperative. State agency report

Jacobs, L., 2009: FHWA/AASHTO Climate Change Adaptation Peer Exchange - December 2009.

Jaroszweski, D., L. Chapman, and J. Pettis, 2010: Assessing the potential impact of climate change on transportation: The need for an interdisciplinary approach. *Journal of Transport Geography*, **18,** 331-335

Kulesa, G., 2003: Weather and Aviation: How Does Weather Affect the Safety and Operations of Airports and Aviation, and How Does FAA Work to Manage Weather-related Effects? *The potential impacts of climate change on transportation*.

Kunkel, K., E. Janssen, L. Stevens, and S. Stevens, 2012a: Climate of the Contiguous United States (draft v0.7). NCA report, 37 pp

Larsen, G., Smith, Wilson, Strzepek, Chinovsky, and Saylor, 2007: Estimating Future Costs for Alaska Public Infrastructure At Risk from Climate Change. report

Larsen, P., S. Goldsmith, O. Smith, M. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18,** 442-457, [Available online at http://linkinghub.elsevier.com/retrieve/pii/S0959378008000216]

Massachusetts Energy and Environmental Affairs, 2011: Massachusetts Climate Change Adaptation Report.

McLaughlin, B., S. Murrell, and S. DesRoches, 2011: Case Study: Assessment of the Vulnerability of Port Authority of NY & NJ Facilities to the Impacts of Climate Change. *TD&I Congress 2011: Integrated Transportation and Development for a Better Tomorrow*, Arlington, VA, American Society of Civil Engineers.

Metropolitan Transportation Authority, cited 2012: Subway and Bus Ridership. [Available online at http://www.mta.info/nyct/facts/ridership/index.htm#atGlance_s]

——, 2012b: MTA Service Advisory, [Available online at http://alert.mta.info/]

Meyer, M., A. Amekudzi, and J. O'Hare, 2010: Transportation Asset Management Systems and Climate Change. *Transportation Research Record: Journal of the Transportation Research Board*, **2160,** 12-20

Meyer, M.D., 2008: Design Standards for US Transportation Infrastructure. Transportation Research Board.

Michigan Department of Transportation, 2012: Climate Change Adaptation Issues in Highway Operations. TRB Webinar

NCA/SLCS Team, 2011: Sea Level Change Scenarios for the U.S. National Climate Assessment (v0.5), 1 pp

New York State, 2011: Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation in New York State. *Annals of the New York Academy of Sciences*, **1244,** 2-649 doi: 10.1111/j.1749-6632.2011.06331.x

New York State Sea Level Rise Task Force, 2010: Report to the Legislature

NIOSH, 1986: Occupational Exposure to Hot Environments: Revised Criteria 1986

NRC, 2008: Potential Impacts of Climate Change on U.S. Transportation, 280 pp. pp. [Available online at http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf]

Oster, C.V. and J. Strong, 2008: *Managing the Skies: Public Policy, Organization, and Financing of Air Navigation.* Ashgate Publishing.

Radow, L. and L. Neudorff, 2011: Transportation Adaptation's Bearing on Planning, Systems Management, Operations, and Emergency Response. *Adapting Transportation to the Impacts of Climate Change: State of the Practice 2011, TRB Circular E-C152*, Transportation Research Board.

Rosenzweig, C., W. Solecki, A. DeGaetano, M. O'Grady, S. Hassol, and P. Grabhorn, 2011b: Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation in New York State. *Annals of the New York Academy of Sciences*, **1244,** 2-649 doi: 10.1111/j.1749-6632.2011.06331.x

Rossetti, M., 2002: Potential Impacts of Climate Change on Railroads. . *Potential Impacts of Climate Change on Transportation: Federal Research Partnership Workshop*, Washington, D.C., Brookings Institute, 11.

Rossetti, M.A. and M. Johnsen, 2011: Weather and Climate Impacts on Commercial Motor Vehicle Safety

Rypinski, A., 2011: Climate Impacts and U.S. Transportation, Technical Input Report 2011-0051

Schrank, D.L., T.J. Lomax, and B. Eisele, 2011: *The Urban Mobility Report.* Texas Transportation Institute, The Texas A&M University System.

Slater, G., 2011: Transportation Climate Adaptation Activities in Maryland *TRB 90th Annual Meeting (January 23-27, 2011)*, Washington, DC, Transportation Research Board.

Stewart, B., J. Walsh, K. Kunkel, L. Stevens, and S. Stevens, 2012: Climate of Alaska (v0.7), 14 pp

Suarez, P., W. Anderson, V. Mahal, and T. Lakshmanan, 2005: Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston Metro Area. *Transportation Research Part D: Transport and Environment*, **10,** 231-244

Tetreault, R., 2011, Interview: AASHTO Climate Brief

The Associated Press, 2012: Corps cuts flow on Missouri River. *USA Today*.

The New York Times, cited 2012: Assessing the Damage from Hurricane Sandy. [Available online at http://www.nytimes.com/interactive/2012/10/30/nyregion/hurricane-sandys-aftermath.html]

The Port Authority of New York & New Jersey, 2012a: Port Authority Updates Conditions at Transportation Facilities. Press Release Number: 174-2012.

——, 2012b: Port Authority continues limited PATH service. Press release number: 189-2012., [Available online at http://www.panynj.gov/press-room/press-item.cfm?headLine_id=1701]

——: Port Elizabeth to Open for Business. Press Release Number: 179-2012. [Available online at http://www.panynj.gov/press-room/press-item.cfm?headLine_id=1691]

U.S. Army Corps of Egineers, 2012, personal communication.

U.S. Army Research and Development Center, 2009: Depth Utilization Analysius for Estimating Economic Activity Supported by Dredging

U.S. Bureau of Economic Analysis, 2011: Fixed Assets and Consumer Durable Goods for 1997–2010. *Survey of Current Business*, 27-40.

VANR, 2012: Tropical Storm Irene: By the Numbers.

Vantuono, W.C.: Hurricane Sandy Devastates NY/NJ area passenger rail systems. [Available online at http://www.railwayage.com/index.php/passenger/commuter-regional/hurricane-sandy-devastates-ny-nj-area-passenger-rail-systems.html#.ULY_5dPjnRc]

Vedenov, D., S. Fuller, B. McCarl, W. Attavanich, and V. Ahmedov, 2011: Effect of Climate Change on Crop Production Patterns With Implications to Transport Flows and Inland Waterways

Washington State University, 2012: *Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy.* Washington State University, Department of Ecology.

WICCI, 2011: Wisconsin's Changing Climate Impacts and Adaptation

Wilbanks, T., S. Fernandez, G. Backus, P. Garcia, K. Jonietz, P. Kirshen, M. Savonis, B. Solecki, L. Toole, M. Allen, R. Bierbaum, T. Brown, N. Brune, J. Buizer, J. Fu, O. Omitaomu, L. Scarlett, M. Susman, E. Vurgin, and R. Zimmerman, 2012: Climate Change and Infrastructure, Urban Systems, and Vulnerabilities. Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment

WSDOT, 2008: Storm-Related Closures of I-5 and I-90: Freight Transportation Economic Impact Assessment Report, Winter 2007-2008. Final Research Report WARD 708.1

Xie, F. and D. Levinson, 2011: Evaluating the effects of the I-35W bridge collapse on road-users in the twin cities metropolitan region. *Transportation Planning and Technology*, **34,** 691-703

Zimmerman, R. and C. Faris, 2010: Infrastructure impacts and adaptation challenges. *Annals of the New York Academy of Sciences*, **1196,** 63-86