

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 affecting 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 on transportation infrastructure, 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 the total costs to the nation's 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.¹ 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, pedestrian/bicycle trails and lanes, locks, canals/channels, light rail, subways, freight and commuter railways, and pipelines, with mixed public and private ownership and management;
- vehicles, such as cars, transit buses, and trucks; transit and railcars and locomotives; ships and barges; and aircraft – many privately owned; and

- 1 • the people, institutions, laws, policies, and information systems that convert infrastructure
2 and vehicles into working transportation networks.

3 Besides being affected by climate changes, transportation systems also contribute to changes in
4 the climate through emissions. In 2010, the U.S. transportation sector accounted for 27% of total
5 U.S. heat-trapping greenhouse gas emissions, with cars and trucks accounting for 65% of that
6 total.² Petroleum accounts for 93% of the nation’s transportation energy use.² This means that
7 policies and behavioral changes aimed at reducing greenhouse gas emissions will have
8 significant implications for the various components of the transportation sector.

9 Weather events influence the daily and seasonal operation of transport systems.^{3,4,5}

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

16 Climate trends affect the design of transport infrastructure, which is expensive and designed for
17 long life (typically 50 to 100 years). The estimated value of U.S. transportation facilities in 2010
18 was \$4.1 trillion.⁶ As climatic conditions shift, portions of this infrastructure will increasingly be
19 subject to climatic stresses that will reduce the reliability and capacity of transportation systems.⁷
20 Transportation systems are also vulnerable to interruptions in fuel and electricity supply, as well
21 as communications disruptions – which are also subject to climatic stresses.^{7,8} For example,
22 power outages resulting from Hurricane Katrina shut down three major petroleum pipelines for
23 two days, and the systems operated at reduced capacities for two weeks.⁹

24 Climate change will affect transportation systems directly, through infrastructure damage, and
25 indirectly, through changes in trade flows, agriculture, energy use, and settlement patterns. If, for
26 instance, corn cultivation shifts northward in response to rising temperatures, U.S. agricultural
27 products may flow to markets from different origins by different routes.¹⁰ If policy measures and
28 technological changes reduce greenhouse gas emissions by affecting fuel types, there will likely
29 be significant impacts on the transportation of energy supplies (pipelines, coal trains, and so on)
30 and on the cost of transportation to freight and passenger users.¹¹

31 Shifts in demographic trends, land use patterns, and advances in transportation technology over
32 the next few decades will have profound impacts on how the nation's transportation system
33 functions, its design, and its spatial extent. As transportation officials shape the future
34 transportation system to address new demands, future climate conditions should be considered as
35 part of the planning and decision-making process.

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

1 too expensive to protect.¹² As new and rehabilitated transportation systems are developed,
2 climate change impacts should be routinely incorporated into the planning for these systems.

3 There will be challenges in adapting transportation systems to climate related changes,
4 particularly when factoring in projected growth in the transportation sector. A National Surface
5 Transportation Policy and Revenue Commission in 2007 forecast the following annual average
6 growth rates: average annual tonnage growth rates of 2.1% for trucks, 1.9% for rail, and 1.2% for
7 waterborne transportation, and an average annual passenger vehicle miles traveled growth rate of
8 1.82% through 2035 and 1.72% through 2055.¹³

9 ***Reliability and Capacity at Risk***

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

14 Global climate change has both gradual and extreme event implications. A gradually warmer
15 climate and increased drought in the Southeast and Southwest will accelerate asphalt
16 deterioration and cause buckling of pavements and rail lines.¹⁴ Streamflows based on
17 increasingly more frequent and intense rainfall instead of slower snowmelt could increase the
18 likelihood of bridge damage from faster-flowing streams.¹⁵ However, less snow in some areas
19 will reduce snow removal costs and extend construction seasons. Shifts in agricultural
20 production patterns will necessitate changes in transportation routes and modes.¹⁶

21 Climate models project that extreme heat and heat waves will become more intense, longer
22 lasting, and more frequent (Ch. 2: Our Changing Climate). By 2080-2100, average temperatures
23 are expected to increase by 3°F to 6°F for the continental U.S., assuming emissions reductions
24 from current trends (B1 scenario), while continued increases in emissions (A2 scenario) would
25 lead to an increase in average temperatures ranging from 5°F in Florida to 9°F in the upper
26 Midwest.¹⁷

27 The impact on transportation systems not designed for such extreme temperatures would be
28 severe. At higher temperatures, expansion joints on bridges and highways are stressed and some
29 asphalt pavements deteriorate more rapidly.¹⁸ Rail track stresses and track buckling will
30 increase.^{14,19} High air temperatures can affect aircraft performance; lift-off limits at hot-weather
31 and high-altitude airports will reduce aircraft operations.²⁰

32 Construction crews may have to operate on altered time schedules to avoid the heat of the day,
33 with greater safety risks for workers.²¹ The construction season may lengthen in many localities.
34 Similarly, higher temperatures (and precipitation changes) are likely to affect transit ridership,
35 bicycling, and walking.^{14,22}

36 Climate change is most pronounced at high northern latitudes. Alaska has experienced a 3°F rise
37 in average temperatures since 1949,²³ double the rest of the country. Winter temperatures have
38 risen by 5°F. On the North Slope, sea ice formerly provided protection to the shoreline against
39 strong fall/winter winds and storms (see Ch. 12: Indigenous Peoples). Retreating ice reduces this
40 protection, eroding the shoreline and endangering coastal villages. Thawing permafrost is

1 causing pavement, runway, rail, and pipeline displacements, creating problems for operation and
2 maintenance, and requiring reconstruction of key facilities.

3 Arctic warming is also projected to allow the seasonal opening of the Northwest Passage to
4 freight shipment.²⁴ Global climate projections to 2100 show extensive open water areas during
5 the summer around the Arctic basin. Retreat of Arctic sea ice has been observed in all seasons
6 over the past five decades, with the most prominent retreat in summer,²⁴ and a limited number of
7 freighters, cruise ships, and smaller vessels have traversed the Northwest Passage for several
8 years.

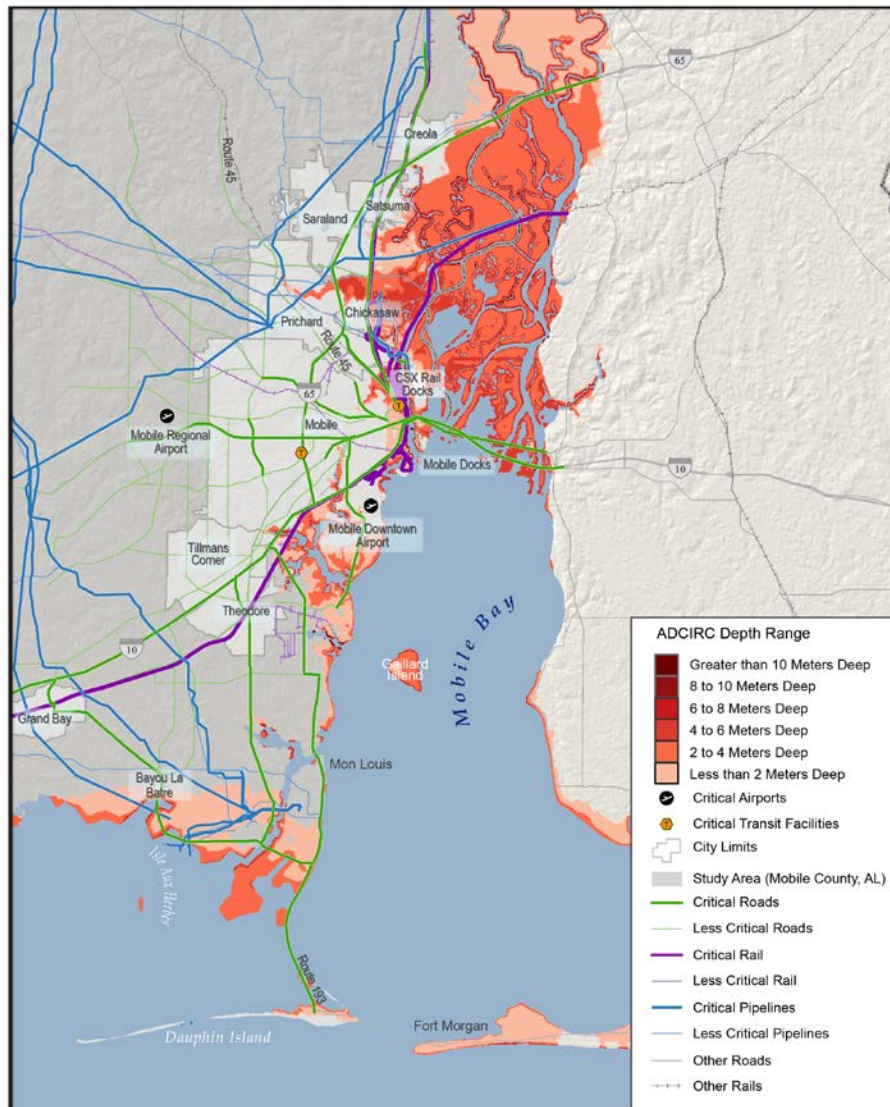
9 **Box 1: Thawing Alaska**

10 Permafrost – soil saturated with frozen water – is a key feature of the Alaskan landscape. *Frozen*
11 permafrost is a suitable base for transportation infrastructure such as roads and airfields. In
12 rapidly warming Alaska, however, as permafrost thaws into mud, road shoulders slump, highway
13 cuts slide, and runways sink. Alaska currently spends an extra \$10 million per year repairing
14 permafrost damage.²⁵

15 A recent study, which examined potential climate damage to Alaskan public infrastructure using
16 results from three different climate models,²⁶ considered 253 airports, 853 bridges, 131 harbors,
17 819 miles of railroad, 4,576 miles of paved road, and 5,000 miles of unpaved road that could be
18 affected by climate change. The present value of additional public infrastructure costs due to
19 climate change impacts was estimated at \$5.6 to \$7.6 billion through 2080, or 10% to 12% of
20 total public infrastructure costs in Alaska. These costs might be reduced by 40% with strong
21 adaptation actions.²⁶

22 -- end box --

Possible Future Flood Depths in Mobile, AL with Rising Sea Level



1

2 **Figure 5.1:** Possible Future Flood Depths in Mobile, AL with Rising Sea Level

3 **Caption:** Many coastal areas in the U.S., including the Gulf Coast, are especially
 4 vulnerable to sea level rise impacts on transportation systems.^{11,27,28} This is particularly
 5 true when one considers the interaction among sea level rise, wave action, and local
 6 geology.²⁹ This map shows that many parts of Mobile, Alabama, including critical roads,
 7 rail lines, and pipelines, would be exposed to storm surge under a scenario of a 30-inch
 8 sea level rise combined with a storm similar to Hurricane Katrina. Not all roads would be
 9 flooded if they merely run through low areas since some are built above flood levels. A
 10 30-inch sea level rise scenario is within the range projected for global sea level rise (Ch.
 11 2: Our Changing Climate, Key Message 10). (Figure source: U.S. Department of
 12 Transportation 2012).³⁰

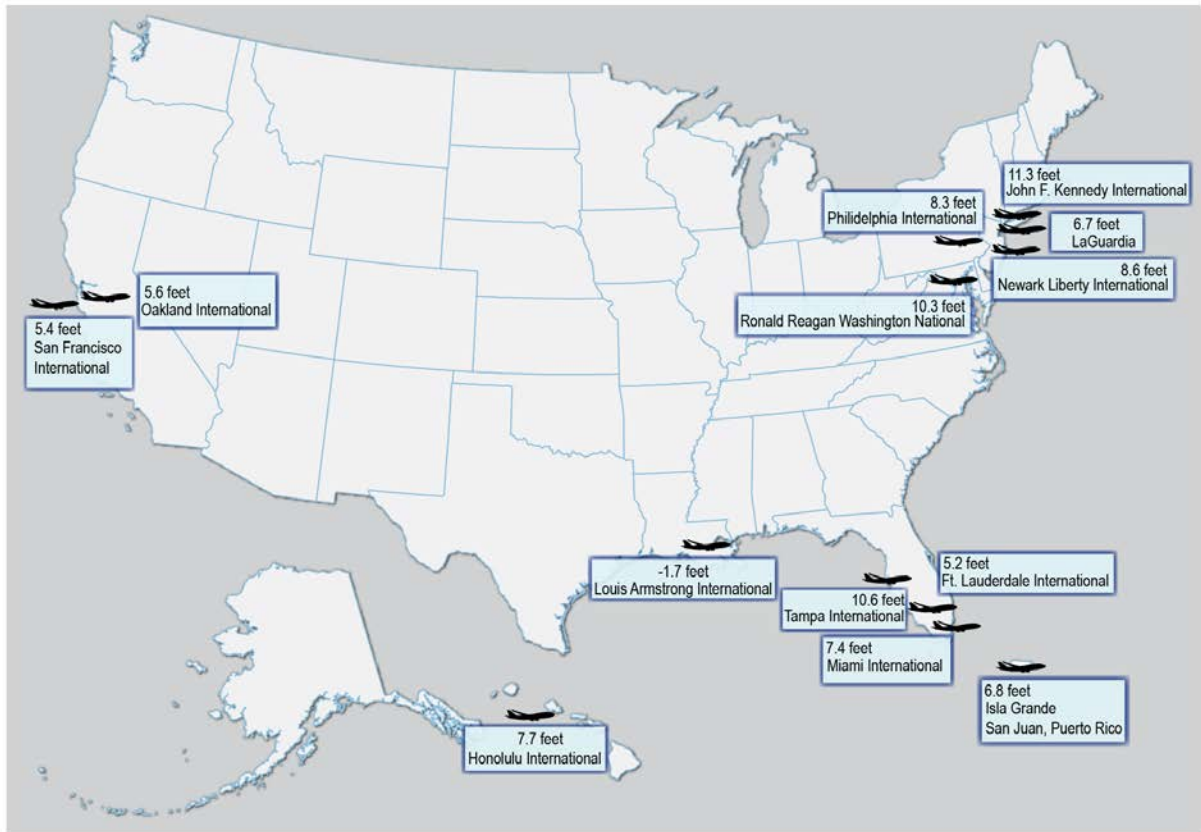
1 *Coastal Impacts*

2 **Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal** 3 **impacts on transportation infrastructure, including both temporary and permanent** 4 **flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.**

5 The transportation impacts of rising global sea level, which is expected to continue to rise by at
6 least an additional 1 to 4 feet by 2100 (see also Ch. 2: Our Changing Climate, Key Message
7 10),³¹ will vary widely by location and geography. When sea level rise is coupled with intense
8 storms, the resulting storm surges will be greater, extend farther inland, and cause more
9 extensive damage. Relative sea level rise will be greater along some coasts (such as Louisiana,
10 Texas, and parts of the Chesapeake Bay), and this will have significant effects on transportation
11 infrastructure, even without the coupling with storms, due to regional land subsidence (land
12 sinking or settling) (Ch. 25: Coasts). Ports and harbors will need to be reconfigured to
13 accommodate higher seas. Many of the nation's largest ports are along the Gulf Coast, which is
14 especially vulnerable due to a combination of sea level rise, storm surges, erosion, and land
15 subsidence.¹¹ Two additional impacts for ports include: inadequate bridge clearance availability
16 with sea level rise for large vessels to pass safely; and second, even if the elevation of the port
17 facility is adequate, any main access road that is not elevated will become more frequently
18 inundated, thus affecting port operations. In 2011, the U.S. imported 45% of total oil
19 consumption, and 56% of those imports passed through Gulf Coast ports.³²

20 More frequent disruptions and damage to roads, tracks, runways, and navigation channels are
21 projected in coastal areas beyond the Gulf Coast. Thirteen of the nation's 47 largest airports have
22 at least one runway with an elevation within 12 feet of current sea levels.³³ Most ocean-going
23 ports are in low-lying coastal areas, including three of the most important for imports and
24 exports: Los Angeles/Long Beach (handles 31% of the U.S. port container movements) and the
25 Port of South Louisiana and the Port of Galveston/Houston (combined handle 25% of the tons
26 handled by U.S. ports).³⁴ Extreme floods and storms associated with climate change will lead to
27 increased movement of sediment and buildup of sandy formations in channels. For example,
28 many federally maintained navigation channels have deteriorated in recent years to dimensions
29 less than those authorized, in part due to floods and storms, which resulted in reduced levels of
30 service that affect navigation safety and reliability.³⁵ Channels that are not well maintained and
31 have less sedimentation storage volume will thus be more vulnerable to significant, abrupt losses
32 in navigation service levels. Additional channel storage capacity that may be created by sea level
33 rise will also increase water depths and increase sedimentation in some channels. (See Ch. 25:
34 Coasts for additional discussion of coastal transportation impacts.)

Airports Vulnerable to Storm Surge



1
2 **Figure 5.2:** Airports Vulnerable to Storm Surge

3 **Caption:** Thirteen of the nation’s 47 largest airports in the U.S. have at least one runway
4 with an elevation within the reach of moderate to high storm surge. Sea level rise will
5 pose a threat to low-lying infrastructure, such as the airports shown here. (Data from
6 Federal Aviation Administration 2012³³).

7 ***Weather Disruptions***

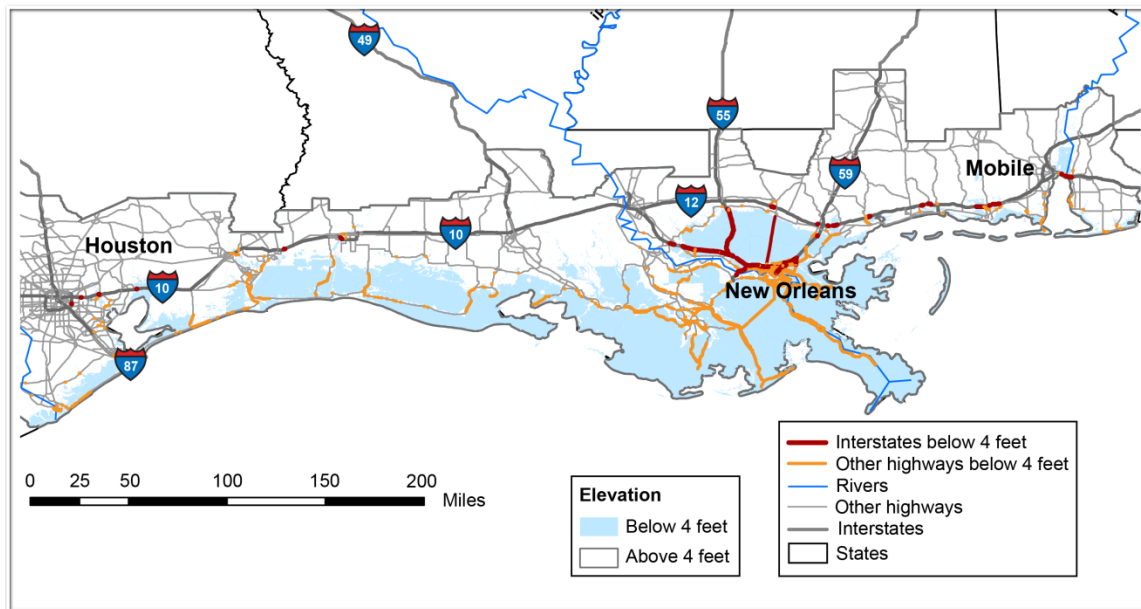
8 **Extreme weather events currently disrupt transportation networks in all areas of the**
9 **country; projections indicate that such disruptions will increase.**

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

1 Inland waterways may well experience greater floods, with high flow velocities that are unsafe
2 for navigation and shut channels down intermittently. Numerous studies indicate increasing
3 severity and frequency of flooding throughout much of the Mississippi and Missouri River
4 Basins.³⁶ Increases in flood risk reflect both changing precipitation and changing land use
5 patterns.³⁷ In the Upper Mississippi/Missouri Rivers, there have been two 300- to 500-year
6 floods over the past 20 years.³⁸ Drought increases the probability of wildfires, which affect
7 visibility severely enough to close roads and airports. Drought can lower vessel drafts on
8 navigable rivers and associated lock and dam pools. On the other hand, less ice formation on
9 navigable waterways has the potential to increase seasonal windows for passage of navigation.

10 The frequency of the strongest hurricanes (Category 4 and 5) in the Atlantic is expected to
11 increase (see Ch. 2: Our Changing Climate, Key Message 8). As hurricanes approach landfall,
12 they create storm surge, which carries water farther inland. The resulting flooding, wind damage,
13 and bridge destruction disrupts virtually all transportation systems in the affected area. Many of
14 the nation's military installations are in areas that are vulnerable to extreme weather events, such
15 as naval bases located in hurricane-prone zones.

Gulf Coast Transportation Hubs at Risk



1

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

3 **Caption:** Within this century, 2,400 miles of major roadway are projected to be
 4 inundated by sea level rise in the Gulf Coast region. The map shows roadways at risk
 5 in the event of a sea level rise of about 4 feet, which is within the range of projections for
 6 this region in this century (see also Ch. 2: Our Changing Climate, Key Message 10). In
 7 total, 24% of interstate highway miles and 28% of secondary road miles in the Gulf Coast
 8 region are at elevations below 4 feet. (Figure source: Kafalenos et al. 2008³⁹).

9 **Box 2: Hurricane Sandy**

10 On October 29, 2012, Hurricane Sandy dealt the transportation systems of New Jersey and New
 11 York and environs a massive blow (See also Ch.16: Northeast; Box on Hurricane Vulnerability;
 12 Ch. 11: Urban; Box on Hurricane Sandy). The damages from Sandy are indicative of what
 13 powerful tropical storms and higher sea levels could bring on a more frequent basis in the future,
 14 and were very much in line with vulnerability assessments conducted over the past four
 15 years.^{40,41,42} All tunnels and most bridges leading into New York City were closed during the
 16 storm. Storm tides of up to 14 feet⁴³ flooded the Queens Midtown, Holland, and Carey (Brooklyn
 17 Battery) tunnels, which remained closed for at least one week (two weeks for the Carey Tunnel)
 18 while floodwaters were being pumped out and power restored. The three major airports
 19 (Kennedy, Newark, and LaGuardia) flooded, with LaGuardia absorbing the worst impact and
 20 closing for three days.⁴⁴

21 Almost 7.5 million passengers per day ride the New York City subways and buses.⁴⁵ Much of the
 22 New York City subway system below 34th Street was flooded, including all seven tunnels under
 23 the East River to Brooklyn and Queens. In addition to removing the floodwaters, all electrical

1 signaling and power systems (the third rails) had to be cleaned, inspected, and repaired. Service
2 on most Lower Manhattan subways was suspended for at least one week,⁴⁶ as was the PATH
3 system to New Jersey.⁴⁷ Commuter rail service to New Jersey, Long Island, and northern
4 suburbs, with more than 500,000 passengers per day,⁴⁵ was similarly affected for days or weeks
5 with flooded tunnels, downed trees and large debris on tracks, and loss of electrical power.⁴⁸ In
6 addition, miles of local roads, streets, underpasses, parking garages, and bridges flooded and/or
7 were badly damaged in the region, and an estimated 230,000 parked vehicles⁴⁹ sustained water
8 damage. Flooded roadways prevented the New York Fire Department from responding to a fire
9 that destroyed more than 100 homes in Brooklyn’s Breezy Point neighborhood.⁵⁰

10 Hurricane Sandy’s storm surge produced nearly four feet of floodwaters throughout the Port of
11 New York and New Jersey, damaging electrical systems, highways, rail track, and port cargo;
12 displacing hundreds of shipping containers; and causing ships to run aground.⁵¹ Floating debris,
13 wrecks, and obstructions in the channel had to be cleared before the Port was able to reopen to
14 incoming vessels within a week.⁵² Pleasure boats were damaged at marinas throughout the
15 region. On a positive note, the vulnerability analyses prepared by the metropolitan New York
16 authorities and referenced above provided a framework for efforts to control the damage and
17 restore service more rapidly. Noteworthy are the efforts of the Metropolitan Transit Authority to
18 protect vital electrical systems and restore subway service to much of New York within four
19 days.

20 The impacts of this extraordinary storm on one of the nation’s most important transportation
21 nodes were felt across the country. Airline schedules throughout the U.S. and internationally
22 were snarled; Amtrak rail service along the East Coast and as far away as Buffalo and Montreal
23 was curtailed; and freight shipments in and out of the hurricane impact zone were delayed. The
24 resultant direct costs to the community and indirect costs to the economy will undoubtedly rise
25 into the tens of billions of dollars (See also Ch. 11: Urban; Box on Hurricane Sandy).

Hurricane Sandy Causes Flooding in New York City Subway Stations



1

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

3 **Caption:** The nation's busiest subway system sustained the worst damage in its 108
4 years of operation on October 29, 2012, as a result of Hurricane Sandy. Millions of
5 people were left without service for at least one week after the storm, as the Metropolitan
6 Transportation Authority rapidly worked to repair extensive flood damage (Photo credit:
7 William Vantuono, Railway Age Magazine, 2012).⁴⁶

8 -- end box --

9 **Risks and Consequences**

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

14 In assessing consequences, the intensity of system use, as well as the existence or lack of
15 alternative routes, must be taken into account. Disabling a transportation facility can have ripple
16 effects across a network, with trunk (main) lines and hubs having the most widespread impacts.⁵³

1 **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

2 **Note:** Table 5.1 relates to overall national expectations based on Angel and Kunkel
 3 2010⁵⁴ and as postulated by chapter authors. This kind of matrix is likely to be most
 4 valuable and accurate if used at the state/regional/local levels. (Source: Matrix format
 5 adapted from McLaughlin et al. 2011).⁵³

6 Any comprehensive assessment of the consequences of climate change would need to encompass
 7 the broad array of factors that influence the nation’s transportation system, and consider changes
 8 in population, society, technology, prices, regulation, and the economy that eventually affect
 9 transportation system performance.⁵⁵ For example, the trend in recent years in the U.S. economy
 10 of adopting just-in-time logistics increases the vulnerability of businesses to day-to-day
 11 disruptions caused by weather and flooding.

1 *Costs and Adaptation Options*

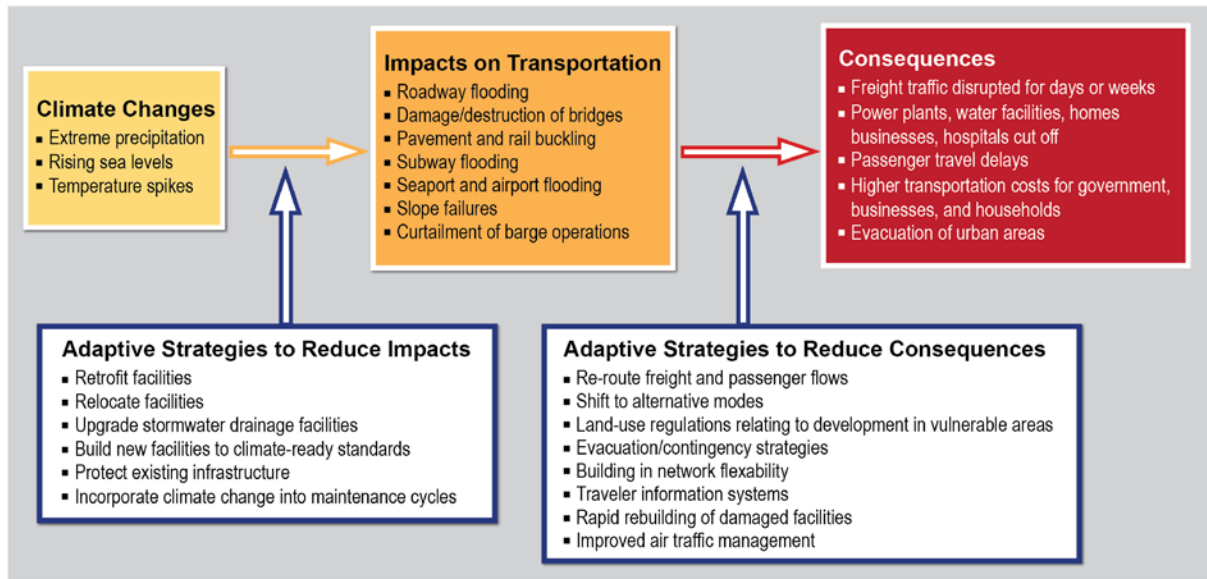
2 **Climate change impacts will increase the total costs to the nation’s transportation systems**
3 **and their users, but these impacts can be reduced through rerouting, mode change, and a**
4 **wide range of adaptive actions.**

5 Adaptation strategies can be employed to reduce the impact of climate change related events and
6 the resulting consequences (See Ch. 28: Adaptation). Consideration of adaptation strategies in
7 the transportation sector is especially important in the following five areas:

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

19

Role of Adaptive Strategies and Tactics in Reducing Impacts and Consequences



1

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

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

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

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

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

19 **Box 3: Winter Storm-Related Closures of I-5 and I-90 in Washington State, 2007–2008**

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

1 The combined economic impact in the I-5 and I-90 corridors was estimated at almost \$75
2 million, of which some \$47 million was associated with the I-5 disruption and \$28 million with
3 the I-90 corridor. Estimated highway damage from the winter storm was \$18 million for state
4 routes and another \$39 million for city and county roads.⁵⁶

5 -- end box --

6 Disruptions to the nation’s inland water system from floods or droughts can, and has, totally
7 disrupted barge traffic. Severe droughts throughout the upper Midwest in 2012 reduced flows in
8 the Missouri and Mississippi Rivers to near record low levels, disrupting barge traffic. While
9 alternative modes, such as rail and truck, may alleviate some of these disruptions, it is
10 impractical to shift major product shipments such as Midwest grain to other modes of
11 transportation – at least in the near term.⁵⁷ While extreme weather events will continue to cause
12 flight cancellations and delays, many weather delays from non-extreme events are compounded
13 by existing inadequacies in the current national air traffic management system.⁵⁸ Improvements
14 in the air traffic system, such as those anticipated in the FAA’s NextGEN
15 (www.faa.gov/nextgen/), should reduce weather-related delays.

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

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

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

31 An important step in devising an adaptation plan is to assess vulnerabilities (Ch. 26: Decision
32 Support; Ch. 28: Adaptation). The Federal Highway Administration funded pilot projects in five
33 coastal states to test a conceptual framework for evaluating risk.⁵⁹ The framework identifies
34 transportation assets, evaluates the likelihood of impact on specific assets, and assesses the
35 seriousness of such impacts.

36 Several state and local governments have conducted additional vulnerability assessments that
37 identify potential impacts to transportation systems, especially in coastal areas. Detailed
38 assessment work has been undertaken by New York City,^{40,42,60} California,⁶¹ Massachusetts,⁶²
39 Washington,⁶³ Florida, and Boston.⁶⁴

1 Box 4: Planning for Climate Change

2 Charlotte County exemplifies how local governments can incorporate aspects of climate change
3 into transportation planning. The Metropolitan Planning Organization in Charlotte County-Punta
4 Gorda, Florida conducted long-range scenario planning that integrated climate change
5 projections.⁶⁵ A “smart growth” scenario that concentrated growth in urban centers was
6 compared with a “resilient growth” scenario that steered development away from areas
7 vulnerable to sea level rise. Planners evaluated the scenarios based on projected transportation
8 performance outcomes and selected a preferred scenario reflecting aspects of each alternative.

9 -- end box --

10 Non-coastal states and regions have also begun to produce vulnerability assessments.
11 Midwestern states including Wisconsin,⁶⁶ Iowa,⁶⁷ and Michigan⁶⁸ have addressed increasing risk
12 of flooded roadways and other impacts.

13 Transit systems are already implementing measures that reduce vulnerability to climate impacts,
14 including rail buckling. Portland’s transit agency has been installing expansion joints at
15 vulnerable locations, improving reliability of rail service.¹⁴ In New York, ventilation grates are
16 being elevated to reduce the risk of flooding.⁴⁰

17 Transportation agencies are incorporating climate change into ongoing design activities. For
18 example, the Alaska Department of Transportation spends more than \$10 million annually on
19 shoreline protection, relocations, and permafrost protection for roadways (see “Thawing Alaska”
20 above).²⁵ In May 2011, the California Department of Transportation (Caltrans) issued guidance
21 to their staff on whether and how to incorporate sea level rise into new project designs.⁶⁹

22 States have begun to integrate climate impacts into Transportation Asset Management, a
23 systematic process for monitoring the conditions of roads and transit facilities.^{18,70} Maryland is
24 working to prioritize assets taking sea level rise and increased storm intensity into account, and is
25 developing a tool to track assets and assess vulnerability.⁷¹ Florida DOT continually monitors
26 conditions on roads and bridges, and is developing a statewide inventory and action plan for
27 high-risk bridges.⁷² Among inland states, Michigan DOT has identified a wide range of
28 operational and asset management changes to adjust to climate change.⁶⁸ Planting street trees has
29 been shown to reduce the urban heat island effect and reduce heat stress on pavement.⁷³

30 Effective stormwater and stream/river management can reduce the risk of flooding for
31 transportation infrastructure. Following Tropical Storm Irene, Vermont state agencies are
32 working on stream and river management to reduce conditions that exacerbate flooding impacts
33 on transportation.⁷⁴

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

35 In August of 2011, Vermont was inundated with rain and massive flooding from Tropical Storm
36 Irene (see also Ch.16: Northeast; Box on Hurricane Vulnerability), closing down 146 segments
37 of the state road system along with more than 200 bridges, and costing an estimated \$175 to
38 \$200 million to rebuild state highways and bridges. An additional 2,000 or more municipal roads
39 and nearly 1,000 culverts were damaged, and more than 200 miles of state-owned rail required
40 repair.⁷⁵

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

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

8 Rich Tetreault of VTrans emphasized that “Certainly we will be looking to right-size the bridges
 9 and culverts that need to be replaced ... Knowing that we do not have the funds to begin
 10 wholesale rebuilding of the entire highway network to withstand future flooding, we will also
 11 enhance our ability to respond” when future flooding occurs.⁷⁴

Tropical Storm Impact on Vermont Road



12

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

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

17 -- end box --

18 Effective asset management requires significant data and monitoring of transportation assets.
 19 Improved weather and road-condition information systems enable transportation system
 20 managers to anticipate and detect problems better and faster – enabling them to close systems if
 21 needed, alert motorists, and dispatch maintenance and snow-removal crews. As Michigan DOT
 22 has noted, an increase in lake-effect snows means that existing models used for snow and ice
 23 removal procedures are no longer reliable, requiring better monitoring and new models, as well
 24 as better roadway condition detection systems.⁶⁸

- 1 Similarly, regular maintenance and cleaning of urban levee and culvert systems reduces the risk
2 of roads and rails being inundated by flooding.
- 3 Extreme weather, such as hurricanes or intense storms, stresses transportation at precisely the
4 time when smooth operation is critical. Effective evacuation planning, including early warning
5 systems, coordination across jurisdictional boundaries, and creating multiple evacuation routes
6 builds preparedness. Identifying areas with high concentrations of vulnerable and special-needs
7 populations (including elderly, disabled, and transit-dependent groups) enhances readiness, as
8 does identifying assets such as school buses or other transit vehicles that can be deployed for
9 households that do not own vehicles.

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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. 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. The author team’s review included a foundational Technical Input Report for the National Climate Assessment, “Climate Impacts and U.S. Transportation.”⁷⁶ 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.

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 affecting the reliability and capacity of the U.S. transportation system in many ways.
Description of evidence base	<p>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.</p> <p>Climate can be described as the frequency distribution of weather over time. Existing weather conditions, flooding, and storm surge demonstrably affect U.S. transportation systems. By changing the frequency of these weather conditions, climate change will inevitably affect the reliability and capacity of U.S. transportations systems. This view is supported by multiple studies of the impacts of weather and climate change on particular transportation systems or particular regions.</p> <p>An aggregate summary of impacts of climate change on U.S. transportation can be found in NRC 2008.⁷ A paper commissioned for NRC 2008 considers specific impacts of various forms of climate change on infrastructure, for example, possible future constraints on infrastructure.¹² The effects of climate on transit systems are summarized in Hodges 2011.¹⁴ The impact of heat and other climate effects on rail systems are described by Hodges 2011 and Rossetti 2002.^{14,19}</p> <p>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 its transportation system, were undertaken by Rosenzweig et al. 2011.⁶⁰ Impacts of SLR on transportation infrastructure for the mid-Atlantic were also discussed in CCSP 2009 SAP 4.1, Ch. 7.²⁷</p> <p>Weather impacts on road systems are discussed in “Climate Impacts and Transportation”⁷⁶ and numerous other sources. Weather impacts on aviation operations are discussed in Kulesa 2003²⁰ and numerous other sources.</p> <p>In addition, the key message and supporting text summarize extensive evidence documented in “Climate Impacts and Transportation.”⁷⁶</p> <p>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.²⁴</p>

10

<p>New information and remaining uncertainties</p>	<p>Recent changes in global sea level rise estimates documented in this report (Ch.2: Our Changing Climate, Key Message 10) have not been incorporated into existing regional studies of coastal areas. In addition, recent research by USGS on the interaction between sea level rise, wave action, and local geology have been incorporated in only a few studies.²⁹</p> <p>Specific estimates 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 presents particular challenges.</p> <p>Impacts of climate on transportation system operations, including safety and congestion, both on road systems and in aviation, have been little studied to date.</p> <p>Future characteristics of society, such as land use patterns, demographics, and the use of information technology to alter transportation patterns, and possible changes to the very nature of future transportation systems themselves all create uncertainty in evaluating climate impacts on the nation’s transportation networks. These societal changes will probably occur gradually, however, allowing the transportation systems to adapt. 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.</p>
<p>Assessment of confidence based on evidence</p>	<p>Confidence is high that transportation systems will be affected by climate change, given current climate projections, particularly regarding sea level rise and extreme weather events.</p>

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

2

- 1 **Chapter 5: Transportation**
- 2 **Key Message Process:** See key message #1.

Key message #2/4	Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.
Description of evidence base	<p>Estimates of global sea level rise are documented in Ch. 2: Our Changing Climate, Key Message 10 of this report.</p> <p>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 (for example, ^{11,28,60}). 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). The most recent projections include a potentially greater rise in global sea level (Ch. 2: Our Changing Climate, Key Message 10).</p> <p>In addition, the key message and supporting text summarize extensive evidence documented in “Climate Impacts and Transportation.”⁷⁶</p>
New information and remaining uncertainties	<p>As noted above, new estimates of global 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 transportation literature reflects recent USGS work on interactions between sea level rise, wave action, and local geology.²⁹</p> <p>New global sea level rise estimates will enable the development of new regional estimates, as well as revision of regional coastal erosion and flood modeling. Such smaller scale estimates are important because transportation and other infrastructure impacts must necessarily be studied in a local context.</p> <p>Generally speaking, modeling of sea level rise impacts using existing USGS National Elevation Dataset (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.²⁷</p> <p>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.</p> <p>Improved modeling is needed on the interactions among sea level rise, storm surge, tidal movement, and wave action to get a better understanding of the dynamics of the phenomena.</p>
Assessment of confidence based on evidence	<p>The authors have high confidence sea levels are rising and storm surge on top of these higher sea levels pose risks to coastal transportation infrastructure.</p>

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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

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- 1 **Chapter 5: Transportation**
- 2 **Key Message Process:** See key message #1.

<p>Key message #3/4</p>	<p>Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.</p>
<p>Description of evidence base</p>	<p>The key message and supporting text summarize extensive evidence documented in “Climate Impacts and Transportation.”⁷⁶</p> <p>Specific regional climate impacts can be identified in each NCA region of the country. Specific climate impacts on transportation by region include:</p> <p>In Alaska, rising temperatures cause permafrost to melt, causing damage to roadbeds, airfields, pipelines, and other transportation infrastructure.²⁵</p> <p>In the Northeast, the Chesapeake region is likely to experience particularly severe local sea level rise due to geologic subsidence,²⁷ 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 increases the potential impacts of sea level rise, storm surge, and precipitation-induced flooding.</p> <p>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,¹¹ as well as the interacting effects of sea level rise and increased precipitation, and extreme events.</p> <p>Midwest transportation infrastructure is subject to changing water levels on the Great Lakes.⁵⁴ Barge traffic disruptions, due to flooding or drought on the Mississippi/Missouri/Ohio river system, might be induced by changes in precipitation patterns.</p> <p>A major concern in the Southwest is that declining precipitation (see Ch. 2: Our Changing Climate, Key Message 5) may induce changes in the economy and society that will affect the transportation systems that serve this region. In the Southwest, rail and highway systems may be exposed to increased heat damage from the higher temperatures. San Francisco Bay, which encompasses two major airports and numerous key transportation links, is at risk for sea level rise and storm surge.⁶¹</p> <p>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.⁶³</p> <p>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).</p>
<p>New information and remaining uncertainties</p>	<p>Recent data clearly show and climate models further substantiate an increase in the intensity of precipitation events throughout much of the U.S.</p> <p>There is a need for a better definition of the magnitude of increased storm intensity so that accurate return frequency curves can be established.</p>

	<p>New regional climate model data from CMIP5 will have a significant impact on regional impact assessments.</p> <p>Climate and impact data desired by transportation planners may be different from the projections generated by regional climate models. This presents a number of challenges:</p> <p>Regional scale transportation impacts are often determined by flood risk and by water flows in rivers and streams. Flooding is, of course, linked to precipitation, but the linkage between precipitation and hydrology is very complex. Precipitation, as projected by climate models, is often difficult to convert into predictions of future flooding, which is what infrastructure designers need.</p> <p>Similarly, an ice storm would be an extreme event for a transportation planner, but the frequency of ice storms has not yet been derived from climate models. More generally, improved methods of deriving the frequency of infrastructure-affecting weather events from regional climate models may be helpful in assessing climate impacts on transportation systems.</p> <p>There are uncertainties associated with the correlation between a warming climate and increased hurricane intensity.</p> <p>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.</p> <p>Planning tools and models can present a step-by-step process for connecting the risk of impact with specific planning strategies such as assessing the vulnerability of existing and proposed infrastructure and then identifying key adaptation practices to address the risk.</p>
<p>Assessment of confidence based on evidence</p>	<p>Given the evidence base and remaining uncertainties, confidence is high that extreme weather events will affect transportation in all areas of the country.</p>

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1 **Chapter 5: Transportation**

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

<p>Key message #4/4</p>	<p>Climate change impacts will increase the total costs to the nation’s transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.</p>
<p>Description of evidence base</p>	<p>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.⁶⁰ A study of the risk to specific infrastructure elements in Alaska²⁶ estimated the net present value of the extra cost from climate change at \$2 to \$4 billion through 2030, and \$4 to \$8 billion through 2080.</p> <p>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.⁷⁵ The economic cost of infrastructure damage is often greater than the cost of repairing or replacing infrastructure.</p> <p>In addition, a recent study of on-road congestion estimates the annual cost of highway congestion at about \$100 billion,⁵ and the Federal Highway Administration estimates that weather accounts for about 15% of total delay.⁴ Similarly, a recent study of aviation congestion indicates that the annual cost of airline delay is about \$33 billion³ 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 increased traffic and aviation delays. Given the scale of current costs, even small changes in delay can have substantial economic costs.</p> <p>There is little published material on transportation adaptation costs and benefits in the literature, in part because “adaptation” is an abstraction (see Ch. 28: Adaptation). 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 this report (for example,^{11,12,69}).</p> <p>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.^{7,69}</p>
<p>New information and remaining uncertainties</p>	<p>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 research is focused on the costs of replacing assets that are affected by extreme weather events, with far less effort devoted to both longer-term impacts of climate change on transportation systems (such as inundation of coastal roads due to sea</p>

	<p>level rise) and to the broader effects of disrupted facilities on network operations or on the community, for example, rerouting of traffic around bottlenecks or evacuation of sensitive populations from vulnerable areas.</p> <p>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 forecasting problem may be more manageable at the local and regional scales at which most transportation decisions are usually made.</p>
<p>Assessment of confidence based on evidence</p>	<p>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.</p>

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