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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

12 Transportation

St. Louis, Missouri

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature. Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences.

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations. In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors.

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services. Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action.

Executive Summary

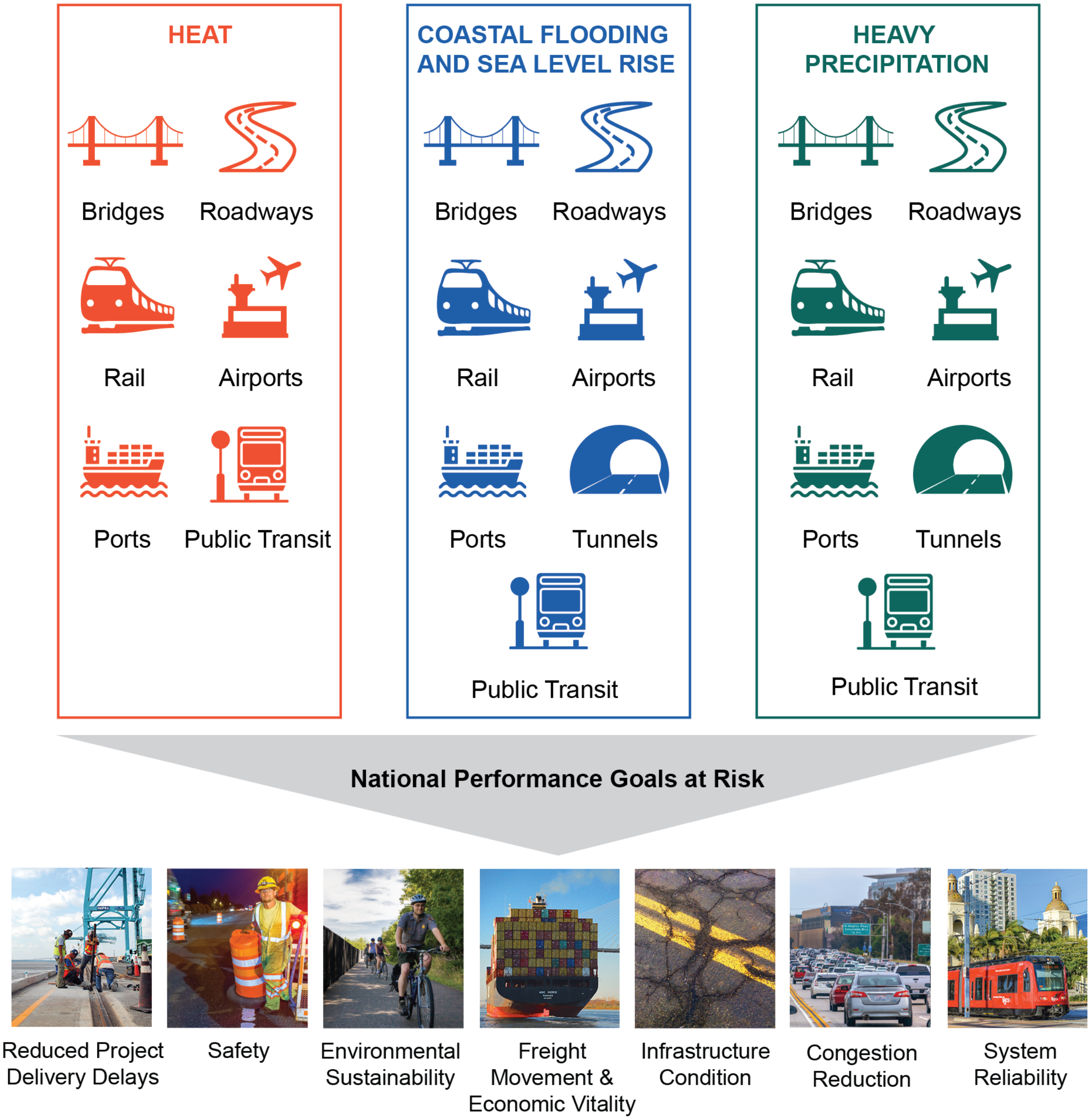
Transportation is the backbone of economic activity, connecting manufacturers with supply chains, consumers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural landscapes. However, the ability of the transportation sector to perform reliably, safely, and efficiently is undermined by a changing climate. Heavy precipitation, coastal flooding, heat, wildfires, freeze–thaw cycles, and changes in average precipitation and temperature impact individual assets across all modes. These impacts threaten the performance of the entire network, with critical ramifications for economic vitality and mobility, particularly for vulnerable populations and urban infrastructure.

Sea level rise is progressively making coastal roads and bridges more vulnerable and less functional. Many coastal cities across the United States have already experienced an increase in high tide flooding that reduces the functionality of low-elevation roadways, rail, and bridges, often causing costly congestion and damage to infrastructure.[1,2] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding. In some regions, the increasing frequency and intensity of heavy precipitation events reduce transportation system efficiency[3] and increase accident risk. High temperatures can stress bridge integrity[4,5] and have caused more frequent and extended delays to passenger and freight rail systems and air traffic.[4,6]

Transportation is not only vulnerable to impacts of climate change but also contributes significantly to the causes of climate change. In 2016, the transportation sector became the top contributor to U.S. greenhouse gas emissions.[7] The transportation system is rapidly growing and evolving in response to market demand and innovation. This growth could make climate mitigation and adaptation progressively more challenging to implement and more important to achieve. However, transportation practitioners are increasingly invested in addressing climate risks, as evidenced in more numerous and diverse assessments of transportation sector vulnerabilities across the United States.

U.S. Transportation Assets and Goals at Risk

Climate Change and Notable Vulnerabilities of Transportation Assets



Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature affect assets (such as roads and bridges) across all modes of transportation. The figure shows major climate-related hazards and the transportation assets impacted. Photos illustrate national performance goals (listed in 23 U.S.C. § 150) that are at risk due to climate-related hazards. *From Figure 12.1 (Source: USGCRP. Photo credits from left to right: JAXPORT, Meredith Fordham Hughes [CC BY-NC 2.0]; Oregon Department of Transportation [CC BY 2.0]; NPS–Mississippi National River and Recreation Area; Flickr user Tom Driggers [CC BY 2.0]; Flickr user Mike Mozart [CC BY 2.0]; Flickr user Jeff Turner [CC BY 2.0]; Flickr user William Garrett [CC BY 2.0] — see https://creativecommons.org/licenses/ for specific Creative Commons licenses).*

State of the Sector

Transportation is the backbone of economic activity, connecting manufacturers with supply chains, consumers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural landscapes. In 2017, the transportation sector added over $400 billion to the U.S. gross domestic product.[9] Transportation is also an important lifeline during emergencies, which may become increasingly common under climate change scenarios (see Kossin et al. 2017[10]). In the event of a disaster, roads, airports, and harbors may serve as key modes of evacuation and often become hubs for emergency personnel and relief supplies.

The transportation sector consists of a vast, interconnected system of assets and derived services, but a changing climate undermines the system's ability to perform reliably, safely, and efficiently (Figure 12.1). Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature impact individual assets across all modes. These impacts threaten the performance (defined by national goals listed in 23 U.S.C. § 150[8]) of the entire network,[11] with critical ramifications for safety, environmental sustainability, economic vitality and mobility, congestion, and system reliability, particularly for vulnerable populations and urban infrastructure. Fortunately, transportation professionals have made progress understanding and managing risks, though barriers persist.

Particularly as impacts compound, climate change threatens to increase the cost of maintaining infrastructure[12] approaching or beyond its design life—infrastructure that is chronically underfunded.[13] Without considering climate impacts, the American Society of Civil Engineers[14] estimates that there is already a $1.2 trillion gap in transportation infrastructure needs. The transportation network is also interdependent on other sectors, such as energy and telecommunications, which have their own climate-related vulnerabilities and existing costs.

Transportation is vulnerable to the impacts of climate change, but it also contributes significantly to the causes of climate change. In 2016, the transportation sector became the top contributor to U.S. greenhouse gas emissions.[7] Low fuel prices, which lead to more driving, coupled with increasing volumes of freight trucking, containerized shipments, and air cargo, underlie the rise in transportation emissions.[15]

The transportation system is rapidly growing and evolving in response to market demand and innovation. Passenger miles traveled on highways and on commuter rail have increased approximately 250% and 175%, respectively, since 1960,[16] and similar trends are expected to continue.[15] Projected population growth of 30% to 50% by mid-century and significant expansion of existing urban centers and surrounding communities[17] will require the transportation system to grow and will place additional demands on the existing network. Long-haul freight is expected to increase 40% by 2040,[18] while air and marine transportation will continue to grow in tandem with economic growth and international trade. This population growth and land-use change can make climate mitigation, environmental sustainability, and adaptation progressively more challenging to implement and more important to achieve.

The shifting future of transportation presents new, pressing complexities and challenges. Transportation innovations such as shared mobility (for example, car sharing, carpooling, and ride-sourcing), transit-oriented development (TOD; that is, efforts to create compact, pedestrian-oriented, mixed-use communities centered around train systems), autonomous and electrified vehicles, Next Generation air transportation technologies, megaships, and hull-cleaning robots are emerging, but their impact on and vulnerability to climate change are still largely uncertain. For example, TOD, one of the older innovative transportation solutions, is very likely to reduce emissions and help build resilience.[19,20,21,22,23] Fuel consumption impacts of autonomous vehicles could vary greatly, depending on how they are deployed.[24] Similarly unclear is the impact that new transportation patterns, combined with deteriorating infrastructure, population growth, and land-use change, will have on the system's ability to adapt to climate change.

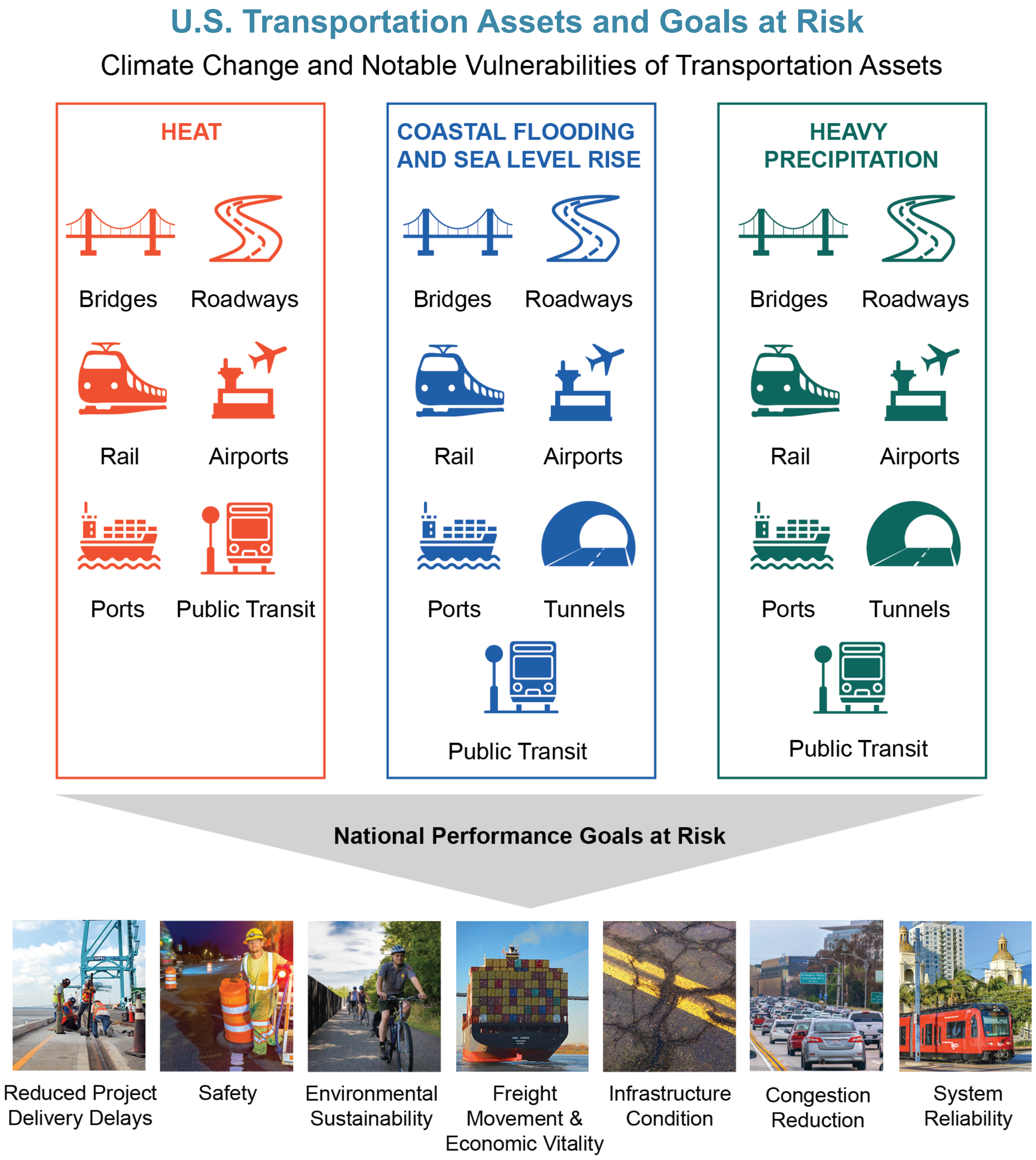


Figure 12.1: Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature affect assets (such as roads and bridges) across all modes of transportation. The figure shows major climate-related hazards and the transportation assets impacted. Photos illustrate national performance goals (listed in 23 U.S.C. § 150[8]) that are at risk due to climate-related hazards. Source: USGCRP. Photo credits from left to right: JAXPORT, Meredith Fordham Hughes [CC BY-NC 2.0]; Oregon Department of Transportation [CC BY 2.0]; NPS–Mississippi National River and Recreation Area; Flickr user Tom Driggers [CC BY 2.0]; Flickr user Mike Mozart [CC BY 2.0]; Flickr user Jeff Turner [CC BY 2.0]; Flickr user William Garrett [CC BY 2.0].

Regional Summary

Precipitation changes are projected to vary across the country, with certainty about impacts much higher in some regions than others (Ch. 18: Northeast).[25] In the Northeast, rainfall volume and intensity have increased[25,26] and may impact transportation performance due to roadway washouts, bridge scour, and heaving or rutting due to freeze–thaw cycles, depending on site-specific conditions.[12,27,28,29] Intense precipitation at Northeast and mid-Atlantic airports has cascading effects on other airports and cargo movement networks, such as trucking and rail, due to delayed or canceled flights and stranded crews.[30,31,32] The projected increases in tropical cyclone wind speeds and rainfall intensity[33] by the end of the century indicate that shipments in Hawai‘i and the Pacific Islands may be interrupted more frequently and for longer periods.[34] Storms also cause erosion and dramatic changes to island coastlines, with associated damages to roadways, harbors, and airports (Ch. 27: Hawai‘i & Pacific Islands, KM 3).

In the Midwest, which has experienced an increase in riverine flooding resulting in long-term interstate freeway closures, future flooding is the main concern for transportation infrastructure (Ch. 21: Midwest, KM 5).[30] In Northeast urban regions, transportation network disruptions from high tide flooding are increasing and further stressing congested networks and storm water management systems (Ch. 18: Northeast, KM 3). Similarly, flooding in the Northwest has repeatedly blocked railways, flooded interstates, and halted freight movement, impacting access to critical services (Ch. 24: Northwest, KM 3 and 5). In the first three months of 2017, Spokane County, Washington, had already spent $2 million more than its yearly budget for road maintenance due to flooding from rapid snowmelt.[35] Flooding in the Pacific Northwest may also threaten access to recreation on federal lands, an economic driver for the region.[36]

Lack of precipitation is also a concern for the transportation network. In the past, high and low extremes in water levels in the Mississippi River and Great Lakes have limited boat traffic, affecting jobs and the ability of goods to get to domestic and international markets[37,38,39] and potentially increasing shipping costs in the future (Ch. 21: Midwest).[40]

In the Midwest, Northeast, Northern Great Plains, and Alaska, in particular, warming winters with fewer extremely cold days[41] and fewer snow and icing events[25] will likely extend the construction season, reduce winter road maintenance demand, and reduce vehicle accident risk.[42,43,44] However, when ice roads that run over a frozen water surface, such as a river or lake, start to thaw and allowable vehicle weight is therefore reduced, trucking and logging industries lose money due to limited access to road networks,[45] thus increasing transport costs (Ch. 26: Alaska, KM 5). Warming winters will also change the timing and location of freeze and thaw events, potentially increasing pavement cracking and pothole conditions in northern states.[12,45] In Alaska, near-surface permafrost thaw is responsible for severe damages to roads, airport runways, railroads, and pipelines (Ch. 26: Alaska).[46]

Climate change is projected to increase the costs of maintaining, repairing, and replacing infrastructure, with regional differences proportional to the magnitude and severity of impacts. Nationally, the total annual damages from temperature- and precipitation-related damages to paved roads are estimated at up to $20 billion under RCP8.5 in 2090 (in 2015 dollars, undiscounted, five-model average) (see the Scenario Products section of App. 3 for more on the RCPs). Inland flooding, projected to increase over the coming century, threatens approximately 2,500 to 4,600 bridges across the United States and is anticipated to result in average annual damages of $1.2 to $1.4 billion each year by 2050 (in 2015 dollars, undiscounted, five-model average).[47]

The transportation chapter of the Third National Climate Assessment highlighted Arctic warming, ports, weather-related disruptions, and adaptation strategies.[48] New research indicates that those findings are still valid concerns for the transportation sector. Some new research highlighted in this chapter includes 1) socioeconomic disparities in response to transportation vulnerabilities, 2) intermodal and cross-sector dependencies and strategies (moving toward a more holistic system as opposed to an asset-based analysis), and 3) communities' challenges, including rural communities, to identify and justify investment in transportation.

The three Key Messages discuss the physical impacts of specific climate hazards on the transportation system, economic implications of interrupted transportation, and the efforts transportation engineers, planners, and researchers are taking to understand and address current and future vulnerabilities.

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature. Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences.

Coastal Risks

Sea level rise (SLR) is progressively making coastal roads and bridges more vulnerable and less reliable. The more than 60,000 miles of U.S. roads and bridges in coastal floodplains are clearly already vulnerable to extreme storms and hurricanes that cost billions in repairs.[49] Higher sea levels will cause more severe flooding and more damage during coastal storms and hurricanes.[50] Recent modeling shows how 1 foot of SLR combined with storm surge can result in more than 1 foot of increased storm surge.[51,52] Low-clearance bridges are particularly vulnerable to increased wave loads from storm surges that can dislodge a bridge deck.[53,54] Since the Third National Climate Assessment, new work has found that SLR has already contributed to damage of one major U.S. bridge during a hurricane: the 3-mile-long bridge carrying I-10 over Escambia Bay, in Pensacola, Florida, was severely damaged during Hurricane Ivan in 2004 (the same mechanism was observed in 2005 after Hurricane Katrina) by wave-induced loads due to a historically high storm surge.[53,55] Ports, which serve as a gateway for 99% of U.S. overseas trade,[56] are particularly vulnerable to climate impacts from extreme weather events associated with rising sea levels and tropical storm activity.[57] SLR and storm surge also threaten coastal airports.[58]

Global average sea levels are expected to continue to rise by at least several inches over the next 15 years and by 1–4 feet by 2100. This 1-to-4-foot range includes the likely projected ranges under all the RCP scenarios.[2] However, a rise of as much as 8 feet by 2100 is scientifically plausible due to possible Antarctic ice sheet instabilities.[2] Coastal infrastructure will be exposed to the effects of relative SLR, which includes vertical land motion in addition to regional variations in the distribution of the global SLR. For example, relative SLR will be higher than the global average on the East and Gulf Coasts of the United States because of the sum of these effects.[2] It is common practice for assessment and planning purposes to develop a range of scenarios of future sea levels that are consistent with these scientific estimates but not specifically based on any one. Scenarios developed by the Federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and

Tools Task Force span the scientifically plausible range and include an Intermediate-Low scenario of 1.6 feet of global average sea level rise by 2100, an Intermediate scenario of 3.3 feet, and an Extreme scenario of 8.2 feet.[59] The relative SLR corresponding to some of these scenarios is used below to estimate increased coastal flooding delays.

Many coastal cities across the United States have experienced an increase in high tide flooding (Ch. 27: Hawai‘i & Pacific Islands),[2] causing areas of permanent inundation and increased local flooding that reduce the functional performance for low-elevation roadways, rail, and bridges and often causing costly congestion and damage to infrastructure.[1,2] In Portsmouth, Virginia, one-third of residents report flooding in their neighborhoods at least a couple of times a year, and nearly half of residents were not able to get in or out of their neighborhoods at least once within the past year due to high tide flooding.[60] On the U.S. East Coast alone, more than 7,500 miles of roadway are located in high tide flooding zones. Unmitigated, this flooding has the potential to nearly double the current 100 million vehicle-hours of delay likely by 2020 (representing an 85% increase from 2010), with a 10-fold increase by 2060 even under the Intermediate-Low SLR scenario (Figure 12.2).[61] US Route 17 in Charleston, South Carolina, currently floods more than 10 times per year and is expected to experience up to 180 floods annually by 2045, with each flood costing the city $12.5 million (in 2009 dollars, undiscounted; $13.75 million in 2015 dollars) (Ch. 19: Southeast).[2] Even if a roadway is not inundated, higher groundwater tables from SLR can impact tunnels and utility corridors and weaken roadway base materials in low-lying coastal regions.[62,63,64,65]

Precipitation and Flooding Risks

In most parts of the United States, heavy precipitation is increasing in frequency and intensity, and more severe precipitation events are anticipated in the future.[25] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding, with impacts including less reliable transportation systems[3] and increased accident risk.[66,67] Extreme precipitation events annually shut down parts of the Interstate Highway System for days or weeks due to flooding and mudslides, as happened in the first five months of 2017 in, for example, northern California (I-80) and southern California (I-880) in January, north central California (I-5) in February, Idaho (I-86) in March, and the central United States including Missouri (I-44 and I-55) in May.

Nationally, projected future increases in inland precipitation over this century will threaten approximately 2,500 to 4,600 bridges by 2050, and 5,000 to 6,000 bridges by 2090, respectively, for the lower and higher scenarios (RCP4.5 and RCP8.5).[47] Bridge failure is most common during unprecedented floods.[68] Damage due to bridge scour can result during less extreme events. This occurs when sediment around piers and abutments is washed away, compromising bridges' structural integrity.[68] Increases in rainfall intensity can accelerate bridge foundation erosion and compromise the integrity and stability of scour-critical bridges.[69]

Freight movement at major international ports can be delayed under extreme weather events that include heavy rains and/or high winds affecting crane operations and truck service.[57] Even without such disruptions, major international trade gateways, hubs, and distribution centers already experience some of the worst congestion in the country.[15]

Transportation systems that are most vulnerable to the recent observed and projected increases in precipitation intensity[25] are those where drainage is already at capacity, where projected heavy rainfall events will occur over prolonged periods, and where changing winter

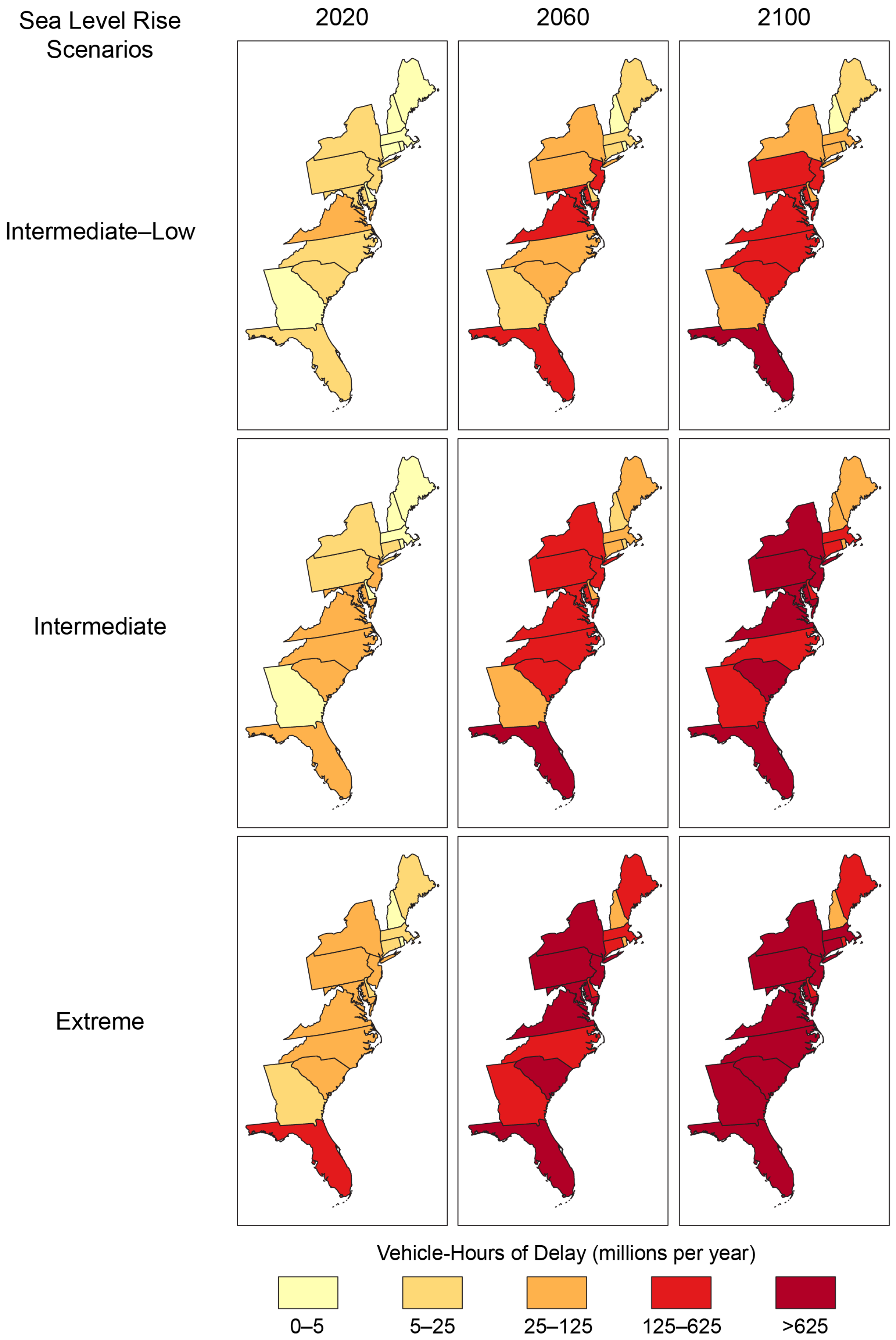

Annual Vehicle-Hours of Delay Due to High Tide Flooding

Figure 12.2: The figure shows annual vehicle-hours of delay for major roads (principal arterials, minor arterials, and major collectors) due to high tide flooding by state, year, and sea level rise scenario (from Sweet et al. 2017).[59] Years are shown using decadal average (10-year) values (that is, 2020 is 2016–2025), except 2100, which is a 5-year average (2096–2100). One vehicle-hour of delay is equivalent to one vehicle delayed for one hour. Source: Jacobs et al. 2018,[61] Figure 3, reproduced with permission of the Transportation Research Board.

precipitation increases transportation hazards from landslides and washouts.[50] In the western United States, large wildfires have increased and are likely to increase further in the future.[70] Debris flows, which consist of water, mud, and debris, are post-wildfire hazards that can escalate the vulnerability of transportation infrastructure to severe precipitation events[71] by blocking culverts and inundating roads.[72]

Rising Temperature Risks

The frequency of summer heat waves has increased since the 1960s, and average annual temperatures have increased over the past three decades; these temperature changes are projected to continue to increase in the future.[41] Across the United States, record-breaking summer temperatures and heat waves have immediate and long-term impacts on transportation. Through the urban heat island effect, heat events may become hotter and longer in cities than in the surrounding rural and suburban areas (Ch. 11: Urban).

High temperatures can stress bridge integrity.[4,5] Extreme temperatures cause frequent and extended delays to passenger and freight rail systems and air traffic when local safe operating guidelines are exceeded.[4,6] Rail tracks expand and weaken, sometimes even bend, under extreme heat.[73] Air transport is sensitive to extreme heat because hotter air makes it more difficult for airplanes to generate lift (the force required for an airplane to take flight), especially at higher elevations, requiring weight reductions and/or longer takeoff distances that may require runway extensions.[74,75]

Heat also compromises worker and public safety. Temperature extremes cause vehicles to overheat and tires to shred, while buckled roadway joints can send vehicles airborne.[76,77] Elevated temperature, combined with increased salinity and humidity, accelerates deterioration in bridges and roads constructed with concrete.[78,79] Higher ambient temperatures and extreme heat events can negatively impact pavement performance and, in turn, increase costs due to material upgrades to accommodate higher temperatures; these costs are only modestly reduced by less frequent maintenance.[12] For example, fixing pavement distress caused by a 2011 heat wave and drought cost the Texas Department of Transportation (DOT) $26 million (dollar year unspecified).[80]

Heat waves and drought require state DOTs to allocate resources to repair damaged pavement. For example, Virginia DOT has dedicated crews who quickly repair roads during extreme heat events.[81] Protocols that govern worker safety limit construction during heat waves[3,76,82] and result in lost productivity.[83] Increased cooling needed to alleviate passenger discomfort and cargo overheating[84] can cause mechanical failures and reduced service, as well as greater greenhouse gas emissions.

An additional 20–30 days per year with temperatures exceeding 90°F (32°C) are projected in most areas by mid-century under a higher scenario (RCP8.5), with increases of 40–50 days in much of the Southeast.[41] In the United States, 5.8 million miles of paved roads are susceptible to increased rutting, cracking, and buckling when sustained temperatures exceed 90°F.[85] Climate change is anticipated to increase the current $73 billion in temperature-induced railway delay costs by $25–$60 billion (in 2015 dollars, discounted at 3%).[6] Heat impacts to airports are expected to increase in the future[74] and, in some cases, are the most critical vulnerability for a region.[86]

It is possible that projected warmer conditions could have some positive effects. Milder winters will lengthen the shipping season in northern inland ports, including the Great Lakes and the Saint Lawrence Seaway.[87,88] The reduction of snow and icing events in southern regions will likely benefit transportation safety, because snow has a significantly higher vehicle accident risk than rainfall.[66,82] Damage to bridges and roads caused by potholes and frost heaves costs hundreds of millions of dollars annually,[4] and changing winter conditions will likely alleviate expenditures in some regions but amplify expenditures in others.[12] However, thawing and freezing rain events may reduce some of the winter maintenance savings. The Alaska Department of Transportation and Public Facilities is anticipating significant challenges due to the effects of warming temperatures on roadways, and it may see increased costs in anti-icing measures in areas that previously rarely had mid-winter thawing and freezing rain.[89]

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations. In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors.

Urban Transportation Network

The urban transportation network can be highly complex and in high demand, with populations relying on many modes of transportation across air, water, and land. U.S. urban highways tend to accommodate more than double the vehicle miles traveled compared to rural highways.[90] A high percentage of the urban population relies on public transit,[91] with greatest usage in the Northeast.[92]

The urban setting tends to amplify climate change impacts, such as flooding, on the performance of the transportation network. Combined sewer and storm sewer systems used in many cities are often not designed to withstand the capacity demand currently experienced during heavy rainfall events or rising high tides (Ch. 11: Urban). This situation is becoming increasingly problematic with more frequent localized flooding, leading to more frequent travel disruptions for commuters, travelers, and freight.[93,94] The effect is compounded in cities with older infrastructure, such as Philadelphia, Miami, Chicago, and Charleston.[94,95,96,97]

Interdependencies among transportation and other critical infrastructure sectors (such as energy) introduce the risk of significant cascading impacts on the operational capacity of the transportation urban network (Ch. 17: Complex Systems, KM 1 and 3). For example, in December 2017, Atlanta's Hartsfield–Jackson International Airport was shut down for nearly 11 hours due to a catastrophic power outage, which caused the cancellation of 1,400 flights.

In an urban environment, there is a greater chance of transportation network redundancy during an extreme weather event. For example, in the New York City metro area after Superstorm Sandy, additional bus service was able to partially compensate for flooded subway and commuter tunnels.[98,99,100] Walking also serves as an essential backstop in urban environments. For cargo, if a portion of a railway suffers damage due to a future flood event, there may be opportunities to redirect freight to highways and/or waterways.

Disruptions to the transportation network during extreme weather events can disproportionately affect low-income people, older adults, people with limited English proficiency, and other vulnerable urban populations.

These populations have fewer mobility options, reduced access to healthcare, and reduced economic ability to purchase goods and services to prepare for and recover from events.[101,102,103]

With growing suburban populations, there is increasing dependence on a variety of transportation systems. For example, in Boston, almost 130,000 people take commuter rail daily.[104] During extreme events, workers in suburban areas often cannot commute to urban offices, leading to economic losses. Evidence of this is seen from the transportation interruptions resulting from storms such as Hurricane Irene, which impacted Philadelphia and New York City, and Superstorm Sandy, which impacted the Northeast Corridor.[105] Telecommuting can mitigate some of these impacts, but a notable component of suburban areas and their economies remains dependent on a reliable transportation system.

Rural Transportation Network

The rural transportation network may lack redundancy, which increases the social and economic dependence on each road and affects agriculture, manufacturing, tourism, and more. Flood events are prolific and exemplify the dependency that rural areas have on their transportation networks. This dependence is illustrated by the 2013 flooding in Boulder, Colorado, where a 200-year flood event (an event having about a 0.5% chance of occurring in a given year) resulted in 485 miles of damaged or destroyed roadways and 1,100 landslide and hillslope failures that cut off many rural towns for weeks.[106,107] In 2016, more than 10 inches of rain caused widespread flooding throughout eastern Iowa and isolated towns along the Cedar River.[108] In 2017, Hurricane Irma entirely cut off road access to the Florida Keys.

Relative to urban areas, rural areas have fewer options for funding the maintenance and rebuilding of roads.[109] During recovery efforts, rural areas have logistical challenges that include the ability to transport the needed construction materials and a dependency on freight networks to support the population.[110] Rural communities face rebuilding challenges that often take additional time and inflict long-term economic damage to residents and local economies.[111]

Resilience Planning

Many federal, state, and municipal agencies have developed frameworks and tools to assess climate change transportation resilience, in some cases in response to legislative and policy actions. There has been an emergence of climate resilience design guidelines for new transportation infrastructure, as well as considerations of climate change in infrastructure regulations and permitting. For example, the City of New York and the Port Authority of New York and New Jersey have issued guidance that instructs project teams on how to incorporate future climate data into capital expenditures.[112,113] However, it is not only large, urban areas that are addressing potential climate impacts to transportation systems. Municipalities in states such as Wisconsin, North Carolina, Mississippi, and Tennessee are including considerations for climate vulnerability and adaptation in long-range planning.[114]

Challenges remain in the development of resilience plans. In the urban environment, issues such as predicting the potential costs of repair and identifying the rippling disruptions are required to inform the investment decision of implementing mitigation strategies.[115] Compared to urban areas, rural areas sometimes struggle to create structures and justify resilience plans, which are both cost effective and address the potential risk from climate change. As illustrated by vulnerable areas such as the

Gulf Coast, increasing storm intensity suggests the need for investments in both improved emergency management planning techniques[116] and increased transportation redundancy. Similarly, in rural mountain areas, where increased precipitation can lead to landslides, the cost of preventive actions may be difficult to justify given the uncertainty of occurrence.[117]

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services. Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action.

Motivation for Vulnerability Assessments

Transportation practitioners are increasingly invested in addressing climate risks, as evidenced in more numerous and diverse assessments of transportation sector vulnerabilities across the United States. These assessments address the direct and indirect reactions to extreme events, funding opportunities and technical assistance and expertise, and the improved availability of climate model outputs. Federal agencies and others have made funding and tools available to evaluate asset-specific and system-wide vulnerabilities in the transportation sector.[118,119,120] For example, the Federal Highway Administration (FHWA) funded 24 pilot studies between 2010 and 2015; these pilots road-tested and advanced frameworks for conducting vulnerability assessments.[120,121,122,123] In the airport sector, the Transportation Research Board supported research and developed guidance for climate risk assessments,[124] adaptation strategies, the integration of climate risk into airport management systems, and benefit–cost analyses. A review of more than 60 vulnerability assessments published between 2012 and 2016 was conducted for this chapter. Results of this review are summarized below and depicted in Figure 12.3.

Vulnerability Assessments Synopsis

Transportation vulnerabilities to climate change can be very different from one location to another. Examining the commonality and differences among place-based vulnerability assessments provides insights into what communities feel are their greatest vulnerabilities. While early climate risk assessment relied on readily available indicators (such as location, elevation, and condition) to screen assets for exposure to climate risks, asset owners and operators have increasingly conducted more focused studies of particular assets that consider multiple climate hazards and scenarios in the context of asset-specific information, such as design lifetime. Of the 60 studies included in the online version of Figure 12.3, roadways were the most commonly assessed asset, followed by bridges and rail. Most assessments used geospatial data to identify vulnerabilities; more sophisticated assessments utilized models as well (for example, Transportation Engineering Approaches to Climate Resiliency, GC2, and the Massachusetts Department of Transportation).[125,126,127] Building on guidance from the FHWA and others,[28] some agencies engaged stakeholders to ground-truth and/or fortify their results.[128]

Most studies focus on multiple climate stressors, including both chronic issues (such as sea level rise) and extreme events (such as flooding, storm surge, and extreme heat). Sea level rise and flooding are the most commonly assessed individual stressors. Although combined risks are rarely assessed, sea level rise and storm surge are sometimes considered together. The majority of

Transportation Vulnerability and Risk Assessments

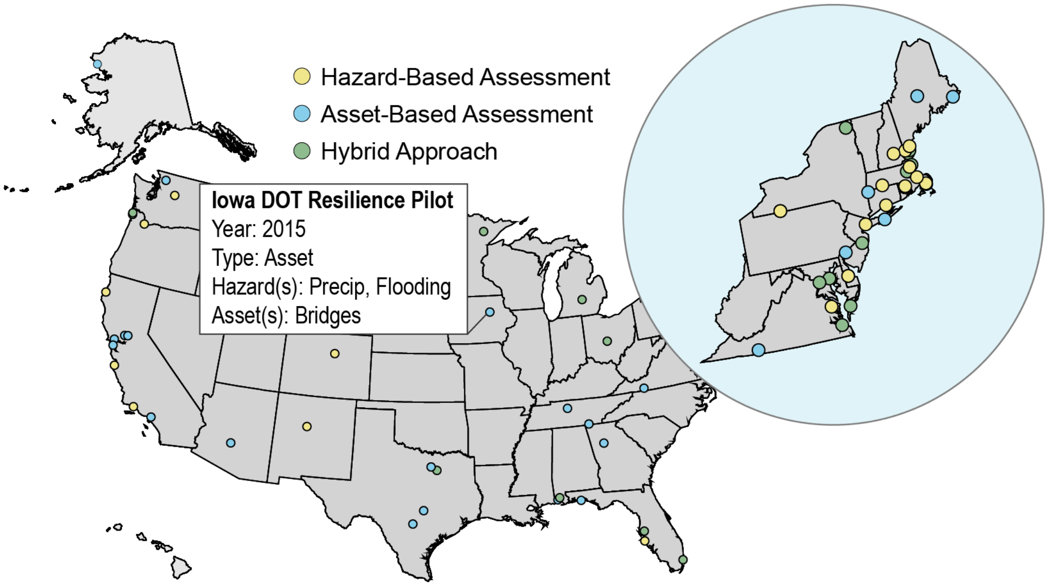


Figure 12.3: This figure shows transportation vulnerability and/or risk assessments from 2012 to 2016 by location. Cumulatively, these vulnerability assessments elucidate national-scale vulnerabilities and progress. Data for the U.S. Caribbean region were not available. See the online version of this map at http://nca2018.globalchange.gov/chapter/12#fig-12-3 to access the complete set of vulnerability and risk assessments. Sources: ICF and U.S. Department of Transportation.

assessments consider only asset-specific vulnerabilities and not transportation system-wide vulnerabilities or vulnerabilities influencing or arising from interdependencies with other sectors (such as water or energy).

The few studies that quantify the costs and benefits from adaptation primarily focus on single assets, rather than the system, and do not quantify both the direct and indirect (such as labor costs) economic costs of transportation system disruptions. The U.S. DOT Hampton Roads Climate Impact Quantification Initiative, currently underway, seeks to demonstrate a replicable approach to considering these costs.[129]

Implementation of Resilience Measures

Proactive implementation of resilience measures is still limited. Resilient solutions for transportation facilities vary greatly depending on the climate stressor, the specifics of a given site, and the availability of funding for implementation (see "Three Case Studies of Resilience Measures for Highway Facilities"). Building the business case for adaptation and aligning the required long-term investments with existing time frames for decision-making is difficult.[3,130,131] Uncertainties associated with projections of future climate hazards in specific geographic locations[130,132,133] and the lack of specific, detailed adaptation strategies[134] make assessment more complicated. However, in the wake of extreme events, some transportation agencies implemented resilience measures to withstand similar events in the future.

Future changes to and uncertainties about transportation technologies and transportation-related behaviors complicate agencies' ability to assess the adaptive capacity of transportation systems, their ability to withstand and recover from a disruption, and opportunities for cost-effective risk mitigation strategies (such as workplace telecommuting policies).

Case Study: Three Case Studies of Resilience Measures for Highway Facilities

In Florida, storm surges overwashing US 98 on Okaloosa Island undermined the highway foundation during Hurricane Ivan in 2004 and then again during other tropical storms in 2005. To prevent damage from overwash in the future, the Florida Department of Transportation installed buried erosion protection along the edge of the road. FHWA's analysis found that this proactive countermeasure was economically justified when it was done in 2006 and, further, that the benefit–cost ratio will quadruple over the next 50 years as sea levels continue to rise.[135]

Shore Road in Brookhaven, New York, is experiencing wave-induced bank erosion during storms. The road elevation is about 2 feet higher than the typical high tide today, and a recent study determined that constructing a coastal marsh can protect the roadway for decades at a low cost while enhancing ecosystems. At a later point, the town could increase the elevation of the road and install more expensive sheet pile walls or rock revetments if needed.[136]

In 2013 in Colorado, precipitation following wildfires caused massive debris flows that overwhelmed culverts and damaged US 24 (see Figure 12.4 for similar case). Recognizing the seriousness of this type of impact, engineering tools driven by future climate simulations were used to evaluate changing wildfire-induced debris flows and precipitation risks to culverts when rebuilding a similar highway (US 34). The best approach identified was to quickly adapt a culvert if and when a wildfire occurs in that watershed, with the goal of upsizing the structure before a rainfall event can cause it to fail. Adapting every culvert to account for wildfire risk would be prohibitively costly, especially given the high uncertainty and low probability that any particular culvert will be impacted by a wildfire over its service life.[72]

Flood Impacts on Colorado Highway

Figure 12.4: Flooding events can result in serious damage to road infrastructure. Here, debris flow covers US Highway 14 (Poudre Canyon) after the High Park Fire in 2012. Photo credit: Justin Pipe, Colorado Department of Transportation.

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Opening Image Credit

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Traceable Accounts

Process Description

We sought an author team that could bring diverse experiences and perspectives to the chapter, including some who have participated in prior national-level assessments within the sector. All are experts in the field of climate adaptation and transportation infrastructure. The team represents geographic expertise in the Northeast, Mid-Atlantic, South, Central, and Western regions, including urban and rural as well as coastal and inland perspectives. Team members come from the public (federal and city government and academia) and private sectors (consulting and engineering), with practitioner and research backgrounds.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops and teleconferences and via email exchanges. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. For additional information on the overall report process, see Appendix 1: Process. The author team also engaged in targeted consultations with transportation experts during multiple listening sessions.

Because the impacts of climate change on transportation assets for the United States and globally have been widely examined elsewhere, including in the Third National Climate Assessment (NCA3),[137] this chapter addresses previously identified climate change impacts on transportation assets that persist nationally, with a focus on recent literature that describes newly identified impacts and advances in understanding. Asset vulnerability and impacts are of national importance because there are societal and economic consequences that transcend regional or subregional boundaries when a transportation network fails to perform as designed; a chapter focus is the emerging understanding of those impacts. Further, place-based, societally relevant understanding of transportation system resilience has been strongly informed by numerous recent local and state assessments that capture regionally relevant climate impacts on transportation and collectively inform national level risks and resilience. The chapter synthesizes the transportation communities' national awareness of and readiness for climate threats that are most relevant in the United States.

Key Message 1

Transportation at Risk

> A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature (*high confidence*). Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences (*high confidence*).

Description of evidence base

Global mean sea level has risen since 1900 and is expected to continue to rise.[2] High tide flooding is increasing and is projected to continue increasing.[1] The peak storm surge levels are expected to rise more than the rise in sea level; models show that if the depth of storm flooding today is A and the rise in sea level between now and a future occurrence of an identical storm is B, then the resulting future storm surge depths can be greater than A + B.[52] The U.S. roads and bridges in the coastal floodplain[49] are vulnerable today, as storms are repeatedly causing damage.[50,53,54,138] Sea level rise is also projected to impact ports,[57] airports,[58] and roads.[63,64,65] High tide flooding currently makes some roads impassable due to flooding[60,61] and is very likely to increase transportation disruptions in the future.[61]

In most parts of the United States, heavy precipitation is increasing in frequency and intensity, and more severe precipitation events are anticipated in the future.[25] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding.[3,25,66,67,69,139] In the western United States, large wildfires have increased and are likely to increase in the future,[70] escalating the vulnerability of transportation infrastructure to severe precipitation events.[71,72]

The frequency of summer heat waves has increased since the 1960s, and average annual temperatures have increased over the past three decades; these temperature changes are projected to continue to increase in the future.[41] Warming temperatures have increased costs[81] and reduced the performance of roads,[80] bridges,[4,5] railways,[4,5,6] and air transport.[3,74,86] Future temperature increases are projected to reduce infrastructure lifetime[78,79,122] and increase road costs.[12] Milder winters will likely lengthen the shipping season in northern inland ports,[87,88] benefit transportation safety,[42,43,44,66,82] and reduce winter maintenance.[4,12,45] In Alaska, however, permafrost thawing will damage roads[46] and increase the cost of roads (Ch. 26: Alaska).

Major uncertainties

Peer-reviewed literature on climate impacts to some assets is limited. Most literature addresses local- or regional-scale issues. Uncertainty in the ranges of climate change projection leads to challenges to quantifying impacts on transportation assets, which have long lifetimes.

Impacts to transportation infrastructure from climate change will depend on many factors, including population growth, economic demands, policy decisions, and technological changes. How these factors, with their potential compounding effects, as well as the impacts of disruptive or transformative technologies (such as automated vehicles or autonomous aerial vehicles), will contribute to transportation performance in the future is poorly understood.

The relationship among increases in large precipitation events and flood-induced infrastructure damage is uncertain because multiple factors (including land use, topography, and even flood control) impact flooding.[140,141,142,143] Hirsch and Ryberg (2012)[144] found limited evidence of increasing global mean carbon dioxide concentrations resulting in increasing flooding in any region of the United States. Archfield et al. (2016)[145] found that flood changes to date are fragmented and that a climate change signal on flood changes was not yet clear.

Description of confidence and likelihood

There is *very high confidence* that sea level rise and increases in flooding during coastal storms and astronomical high tides will lead to damage and service reductions with coastal bridges, roads, rails, and ports.

There is *high confidence* that heavy precipitation events have increased in intensity and frequency since 1901 (with the largest increase seen in the Northeast); this trend is projected to continue.[25] There is *medium confidence* that precipitation increases will lead to surface and rail transit delays in urban areas. There is *medium confidence* that flood-induced damages to roads and bridges will increase.

Rising temperatures and extreme heat (*high confidence*) will damage pavement and increase railway and air transit delays. However, the actual magnitude of those impacts will depend on technological advancements and policy decisions about design and operations.

Key Message 2

Impacts to Urban and Rural Transportation

> Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations (*high confidence*). In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors (*high confidence*).

Description of evidence base

The Key Message is largely supported by observation and empirical evidence that is well documented in the gray (non-peer-reviewed) literature and recent government reports. Because this is an important emerging area of research, the peer-reviewed scientific literature is sparse. Hence, much of the supporting materials for this Key Message are descriptions of impacts of recent events provided by news organizations and government summaries.

Many urban locations have experienced disruptive extreme events that have impacted the transportation network and led to societal and economic consequences. Louisiana experienced historic floods in 2016 that disrupted all modes of transportation and caused adverse impacts on major industries and businesses due to the halt of freight movement and employees' inability to get to work.[146] The 2016 floods that affected Texas from March to June resulted in major business disruption due to the loss of a major transportation corridor.[147] In 2017, Hurricane Harvey affected population and freight mobility in Houston, Texas, when 23 ports were closed and over 700 roads were deemed impassable.[148] Consequences of extreme events can be magnified when events are cumulative. The 2017 hurricanes impacting the southern Atlantic and Gulf Coasts and Puerto Rico created rising freight costs because freight carriers had to deal with poor traveling conditions, an unreliable fuel stock, and limited exports for the return trip.[149,150] Low-income populations have been linked to differences in perceived risks associated with an extreme event, in how they respond, and in their ability to evacuate or relocate.[151] Delays in evacuations can potentially lead to significant transportation delays, affecting the timeliness of first responders and evacuations. National- and local-level decision-makers are considering strategies during storm recovery and its aftermath to identify and support vulnerable populations to ensure transportation and access to schools, work, and community services (for example, the 2016 Baton Rouge flood event).

Similar to the urban and suburban scenarios, rural areas across the country have also experienced disruptions and impacts from climate events. Hurricane Irene resulted in the damage or destruction of roads throughout New England, resulting in small towns being isolated throughout the region.[152] Similarly, Hurricane Katrina devastated rural community infrastructure across the Gulf

Coast, which resulted in extended periods of isolation and population movement.[153] Lesser-known events are also causing regular impacts to rural communities, such as flood events in 2014 in Minnesota and in 2017 throughout the Midwest, which impacted towns for months due to damaged road infrastructure.[154,155]

Although flooding events and hurricanes receive significant attention, other weather-based events cause equal or greater impacts to rural areas. Landslide events have isolated rural communities by reducing them to single-road access.[156,157] Extreme heat events combined with drought have resulted in increases in wildfire activity that have impacted rural areas in several regions. The impacts of these wildfire events include damage to infrastructure both within rural communities and to access points to the communities.[158]

As documented, rural communities incur impacts from climate events that are similar to those experienced in urban and suburban communities. However, rural and isolated areas experience the additional concerns of recovering from extreme events with fewer resources and less capacity.[111] This difference often results in rural communities facing extended periods of time with limited access for commercial and residential traffic.

Major uncertainties

Realized societal and economic impacts from transportation disruptions vary by extreme event, depending on the intensity and duration of the storm; pre-storm conditions, including cumulative events; planning mechanisms (such as zoning practices); and so on. In addition, a combination of weather stressors, such as heavy precipitation with notable storm surge, can amplify effects on different assets, compounding the societal and economic consequences. These amplifications are poorly understood but directly affect transportation users. Interdependencies among transportation and other lifeline sectors can also have significant impacts on the degree of consequences experienced. These impacts are also poorly understood.

Description of confidence and likelihood

There is *medium to high confidence* that the urban setting can amplify heat.[159] There is also *medium to high confidence* that transportation networks are impacted by inland and coastal flooding.[70] There is *medium confidence* that socioeconomic conditions are strongly related to a population's resilience to extreme events.[151]

There is *high confidence* that impacts to the transportation network from extreme events are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations (*medium confidence*). In the absence of intervention, projected changes in climate will likely lead to increasing transportation challenges as a result of system complexity, aging infrastructure with hundreds of billions of dollars in rehabilitation backlogs,[13] and dependency across sectors.

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services (*very high confidence*). Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action (*high confidence*).

Description of evidence base

Chapter authors reviewed more than 60 recently published vulnerability assessments (details and links available through the online version of Figure 12.3) conducted by or for states and localities. The research approach involved internet searches, consultations with experts, and leveraging existing syntheses and compilations of transportation-related vulnerability assessments. The authors cast a broad net to ensure that as many assessments as possible were captured in the review. The studies were screened for a variety of metrics (for example, method of assessment, hazard type, asset category, vulnerability assessment type, economic analysis, and adaptation actions), and findings were used to inform the conclusions reached in this section.

Major uncertainties

Most of the literature and the practitioner studies cited for Key Message 3 were gray literature, which is not peer-reviewed but serves the purpose of documenting the state of the practice. This section was not an assessment of the science (that is, the validity of individual study results was not assessed) but surveyed how transportation practitioners are assessing and managing climate impacts. The conclusions are not predicated on selection of or relative benefits of specific modeling or technological advances.

Practitioners' motivations underlying changes in the state of the practice were derived from information in the studies and from cited literature. The authors of this section did not survey authors of individual vulnerability studies to determine their situation-specific motivations.

Description of confidence and likelihood

There is *high confidence* regarding the efforts of state and local transportation agencies to understand climate impacts through assessments like those referenced in Figure 12.3. There is *medium confidence* in the reasons for delay in implementing resilience measures and the motivations for vulnerability assessments. There is no consensus on how emerging transportation technologies will develop in the coming years and how this change will affect climate mitigation, adaptation, and resilience.

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