Fifth National Climate Assessment: Chapter 13

Transportation

Chapter 13. Transportation

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Introduction

Transportation is fundamental to improving the quality of life in the United States and is a key enabler of economic and social activity for our communities. Transportation and mobility systems are more than a collection of modes (walking, cycling, cars, trucks, buses, trains, planes, and watercraft) to move people and goods in urban and rural environments. They are also a catalyst for change and offer an opportunity to reduce the impacts of a changing climate. Investments in transportation systems are linked to safety, environmental, social, and economic outcomes.

The transportation sector is experiencing rapid changes involving technologies, behaviors, workforce, supply chains, and logistics, all of which face increasing risks posed by climate hazards. Previous assessments highlighted risks arising from transportation investments that did not consider climate change. Challenges remain in managing the existing transportation system within a changing climate while planning for future transport needs with fewer negative impacts on the environment and communities. Historical, auto-centric land-use patterns make transitions to low-carbon transportation challenging (Ch. 12). These conditions necessitate that decision-makers be informed by the best data, science, and business practices, as well as by meaningful engagement with the most affected communities, to make sound short- and long-term transportation investments.

Our Nation's transportation system operates over a vast, unique geographic scale and serves a diverse set of users. It is a major emitter of greenhouse gas (GHG) emissions but is also vulnerable to climate hazards. Making transportation investments that are sustainable, climate-resilient, evidence-based, and equitable involves risk assessment and detailed dynamic analysis of long-term costs and impacts. Science and technology investments can enable rapid implementation of climate-informed decisions and analyses that incorporate a range of social, policy, finance, and engineering considerations toward improving mobility and increasing mobility options in urban and rural communities.

A lower-emissions transportation sector would mitigate GHG emissions, reduce the amount of carbon embedded in deployed materials, and promote cleaner air and healthier communities. However, such a transformation will involve trade-offs, with some negative impacts. Adaptation and mitigation strategies will differ by location. Inclusive decision-making and data-informed processes will help ensure that such impacts are not borne disproportionately by already overburdened communities.

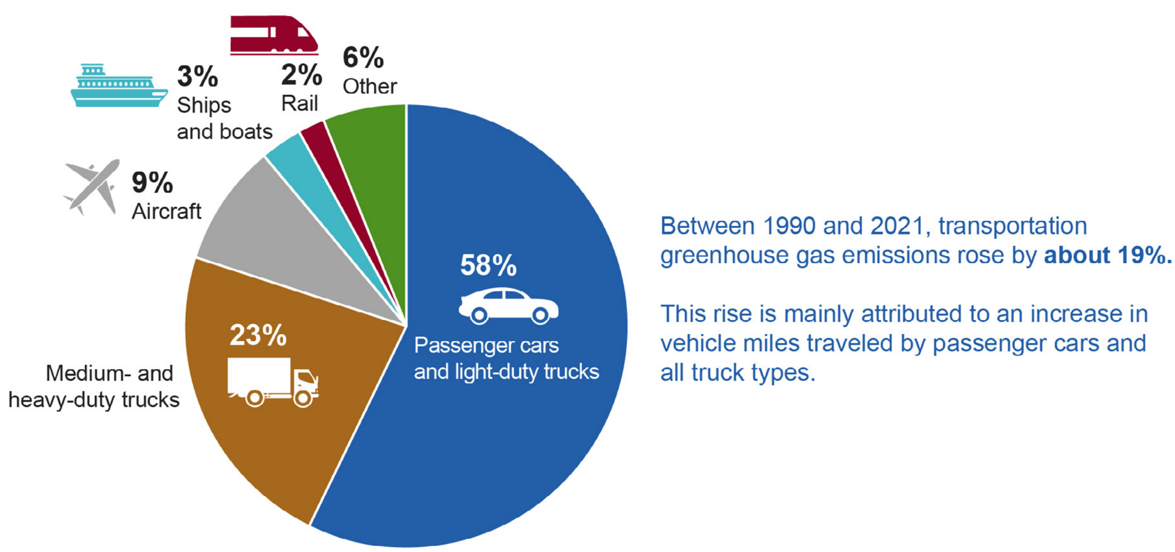
Key Message 13.1

Limiting Transportation Sector Emissions and Integrating Climate Projections Can Reduce Risks

The transportation sector is the largest source of greenhouse gas emissions in the United States, although transportation emissions sources are changing (*very high confidence*). The sector also faces increasing risk from climate-related extreme weather (*very high confidence*). Incorporating climate projections and adaptation and resilience best practices into transportation planning, design, operations, and maintenance can reduce such risks to the sector (*very high confidence*).

The transportation sector is the largest source of GHG emissions in the United States, accounting for 28.5% of total national emissions in 2021 (Figure 13.1). Carbon dioxide (CO_2) remains the dominant GHG in the sector.[1] Limiting global warming to 1.5°C (2.7°F) above preindustrial levels would require a path toward achieving net-zero GHG emissions by 2050.[2] Yet under current policy as of November 2021, projections of US transportation sector energy use and GHG emissions in 2050 are similar to current levels.[3] These projections assume continued increases in freight demand and in the number of miles traveled by vehicle per person, as well as existing powertrain trends. Other studies anticipate a more rapid switch to lower-GHG-emitting technologies resulting from declining costs of electric powertrains and other technologies, in part resulting from federal and state policy changes.[4,5,6,7]

2021 Greenhouse Gas Emissions from US Domestic Transportation by Mode



Transportation remains the largest source of emissions in the US, with cars and light-duty trucks as the largest contributors.

Figure 13.1. Greenhouse gas (GHG) emissions from the US domestic transportation sector rose by about 19% between 1990 and 2021 and remain the largest source of total national GHG emissions, with passenger cars and all types of trucks being the most significant contributors to the rise in transportation emissions. "Other" refers to buses, motorcycles, pipelines, and lubricants. Numbers do not add up to 100% due to rounding. Figure credit: Arizona State University and Texas Tech University. See figure metadata for additional contributors.

Multimodal planning is done at the Metropolitan Planning Organizations (MPO) and/or state level and guided by input from many stakeholders. It involves a comprehensive assessment of transportation needs and includes public involvement to address the needs of multiple users. This includes encouraging increased mass transit use and active modes of transportation such as walking or biking.[8,9,10,11,12] Roadmaps to meet 2050 net-zero emissions targets often include extensive efforts to replace passenger, transit, and freight vehicles with electric vehicles (EVs), which will raise electricity demand (Chs. 5, 32). Some state governments and nonprofits are encouraging the use of low-carbon fuels like hydrogen and biofuels for heavy-duty and hard-to-electrify vehicles, as well as for waterborne transportation modes and aircraft (Ch. 32). Although increasing efforts to electrify vehicles could reduce fossil fuel emissions, consideration must also be given to the challenges posed by this change, such as increased strain on energy grids; transitioning electricity generation from fossil fuels to renewable resources for the purpose of charging EVs; and repurposing, recycling, and safe disposal of EV batteries (KM 13.4; Ch. 17).

The COVID-19 pandemic briefly reduced GHG emissions from the transportation sector, but emissions have mainly rebounded to pre-pandemic levels (KM 13.3; Focus on Compound Events; Focus on COVID-19 and Climate Change).[13,14,15,16] Passenger cars currently contribute the most to transportation emissions; however, the share of emissions from heavy trucks and non-road sources (e.g., trains, airplanes, and ships) is expected to grow due to increasing demand (Ch. 10). Heavy trucks and non-road vehicles use fuels that are more polluting or could cause greater GHG emissions compared to passenger cars (e.g., diesel, jet fuel).[17,18] Expanding reliance on heavy-truck freight could offset any gains in fuel efficiency, resulting in a net increase in GHG emissions by 2050.[18] However, the costs of zero-emissions heavy-duty vehicles are changing rapidly.[19]

Similarly, the aviation sector could see a 50% increase in fuel use between 2020 and 2050 because of growing numbers of flights, even with advanced engine technologies.[17] For example, the Federal Government's Sustainable Aviation Fuel (SAF) Grand Challenge brings together the efforts of the Department of Energy, the Department of Transportation (DOT), the Department of Agriculture, and other federal agencies to reduce the cost, enhance the sustainability, and expand the production of SAF. This effort aims to produce SAF that achieves a minimum of a 50% reduction in life-cycle GHG emissions compared to conventional fuels and has a long-term goal of supplying sufficient SAF to meet 100% of aviation fuel demand by 2050.[20] Emissions-reductions efforts consider both CO_2 and non-CO_2 GHGs.[17]

Climate change and extreme weather events have a negative impact on transportation assets and human safety, often disproportionately affecting socially vulnerable populations (e.g., EPA 2021[21]). Examples of extreme weather events that caused significant transportation-related impacts in 2021 alone include debris flows and flooding after California wildfires, the winter storm in Texas, and Hurricanes Elsa, Florence, and Ida, which caused several deaths and billions of dollars in damages to the East Coast and Louisiana.[22]

Strategies that incorporate climate data and projected future impacts into analyses to support the full range of transportation processes (planning and management of assets over their life cycles, to include considerations of design, construction, operations and maintenance, and user needs) have the potential to reduce risks and costs over the long term (Ch. 31; Figures 31.5, 22.15; KM 12.2). Failure to adapt the transportation network to the impacts of climate change could be costly (e.g., Chinowsky et al. 2013;[23] Schweikert et al. 2015;[24] Neumann et al. 2021[25]). In particular, projected changes in temperature and precipitation, sea level rise, inland water level rise or fall, and storm surge are expected to significantly affect railroads, roads, ports, airports, and other transportation-related riverine and coastal properties in the United States (Ch. 12). Transportation planners are increasingly using analytical frameworks and tools to understand the vulnerabilities of their networks in pursuing a more resilient future (Table 13.1), although the focus on climate adaptation and resilience in transportation varies widely from region to region and state to state (KM 26.5).[26,27,28]

Table 13.1. Climate and Transportation Vulnerabilities

A selection of climate hazards and resulting transportation vulnerabilities are shown. Columns show selected climate hazards, and rows show individual transportation systems and the associated impacts on them. In some cases, possible adaptations to the vulnerabilities are included. Cells with few bullets represent the scarcity of research and not the lack of impact or vulnerability from climate hazards.

Transport Mode	Extreme Temperatures	Storms	Drought	Fire
Active transport (walking and biking)	• Shift from active transport to vehicle or public transport[29] • Adverse health impacts for walkers and cyclists (KM 15.1)[29]	• Shift from active transport to vehicle or public transport[30] • Obstructions and infrastructure damage[30]	• Adverse health impacts for walkers and cyclists due to degraded air quality[31]	• Shift from active transport to vehicle or public transport[32] • Reduced active transport due to short- and long-term health impairments[32]
Aviation	• Runway damage from heat and thawing permafrost[33,34] • Altered flight schedules[35] • Increased insect activity and chance of bird strikes[36,37,38]	• Coastal airport water intrusion[34,39]	• Soil subsidence[40] • Increased dust storm risk[41]	• Increased risk of flooding due to loss of ground cover vegetation[42]
Roadways	• Cracking, buckling, and rutting from heat and permafrost thaw[34,40] • Unsafe working conditions (KM 15.1)[33] • Increased maintenance frequency[43,44,45]	• Damage from flooding, erosion, saturated soil, and sea level rise (Ch. 9)[34,40,43] • Increased risk of landslides[43] • Reduced life cycle from repeated runoff events[46] • Travel lanes and bus routes blocked or rerouted due to flooding[28]	• Reduced pavement integrity due to subsidence, collapsible soils, and increased groundwater pumping[40,43] • Reduced slope stability due to decreased roadside seeding uptake[47] • Emergency bridge maintenance[48] • Reduced visibility and increased closures from dust storms[41]	• Road closures and reduced visibility[40] • Obstructions and debris flows (KM 6.1)[49] • Increased chance of runoff[26,43] • Reduced slope stability due to burn scar[50]
Rail	• Buckling of rails (KM 5.1)[34,40] • Reduced train speeds[51] • Catenary line sag[52]	• Flooding of bridges, tunnels, and low-lying rails[33,34] • Damage from landslides[52]	• Changes in soil stability affecting track geometry and integrity[53]	• Damaged equipment[54] • System disruption and rerouting[54]
Pipelines	• Structural damage due to permafrost thaw (KM 5.1)[55]	• Overloaded drainage systems[40] • Pipeline shifting, exposure, and fracture due to heavy precipitation[34]	• Broken pipelines due to ground subsidence[34]	• Fire-induced toxicity in plastic water systems[56] • Weakened pipelines due to increased runoff and debris flows[57]
Waterborne	• Reduced problems with ice accumulation and increased access to ports (Ch. 10)[34] • Longer shipping seasons[34]	• Port damage due to increased storm surges and tides[34] • River flooding[34]	• Reduced vessel carrying capacity due to lower water levels[34] • Disrupted river transport due to inconsistent river flows (Chs. 22, 24)[33,34]	• Disruption of port operations due to electricity and supply chain disturbances[58,59]

Tools and guidelines help organizations plan for the impacts of climate change, although individual agencies must still take the initiative to use them and challenge existing planning assumptions. Examples include the Federal Highway Administration (FHWA) Vulnerability Assessment and Adaptation Framework,[27] which can help transportation agencies assess their infrastructure's vulnerability to extreme weather and climate impacts. Another is the US DOT's Vulnerability Assessment Scoring Tool,[60] designed to help transportation planners conduct a quantitative, indicator-based screening of transportation system vulnerabilities to climate stressors, such as sea level rise, changes in precipitation, and higher temperatures. A 2021 study by the Transportation Research Board provided a risk-based decision support framework to inform quantitative methods for measuring resilience benefits.[61] Additional research could help model asset deterioration and vulnerability. However, Colorado DOT and Utah DOT pilot studies followed similar risk-based frameworks.[61]

The FHWA has deployed multiple climate-resilience efforts, including the Resilience and Durability to Extreme Weather Pilot Program, to partner with state departments of transportation, metropolitan planning organizations, and others, with the goal of evaluating the vulnerability of regional transportation assets to extreme weather events.[62] The Houston–Galveston Metropolitan Planning Organization participated in this pilot program and found that 13% of freeway miles and 12% of major road miles were highly vulnerable to flooding, storm surge, and sea level rise.[63]

The FHWA pilot program also included the three-county Tampa Bay region in Florida—one of the country's most inundation-vulnerable areas, with frequent storms and persistent flooding. The Hillsborough County Metropolitan Planning Organization found that when factoring in near-future projected sea level rise, 25% of major roads in the region could be impacted in a Category 3 hurricane.[64]

Several state departments of transportation have used some or parts of these frameworks to perform detailed vulnerability assessments and to understand the condition of their assets and risks from climate threats. These efforts may also be driven by state legislation, such as in California and New York,[65,66] by bottom-up approaches at individual state and local agencies. The California Department of Transportation (Caltrans) found that 20% of bridges, 19% of large culverts, 20% of small culverts, and 18% of roadway segments assessed and managed by Caltrans were rated in the highest risk category. This indicates that a large proportion of Caltrans infrastructure is at risk of damage or destruction due to increased storm surge, extreme floods, cliff erosion, extreme temperatures, and effects of wildfires.[43,67,68,69,70,71,72,73,74,75,76,77,78] California has recently mapped coastal transportation infrastructure vulnerable to 3 feet of sea level rise in Los Angeles and San Francisco and is considering a range of adaptation strategies, including nature-based solutions (Chs. 9, 28). Similar efforts have been completed by other states (including Washington, Tennessee, and Maryland) and subnational authorities.

Many agencies and organizations across the Nation have also initiated efforts to address the impacts of climate on a variety of transportation systems. While many of these are still in the initial stages of development, opportunities exist to improve on lessons state and local agencies have learned from the pilot programs at the local level (Ch. 12).[17,28,79]

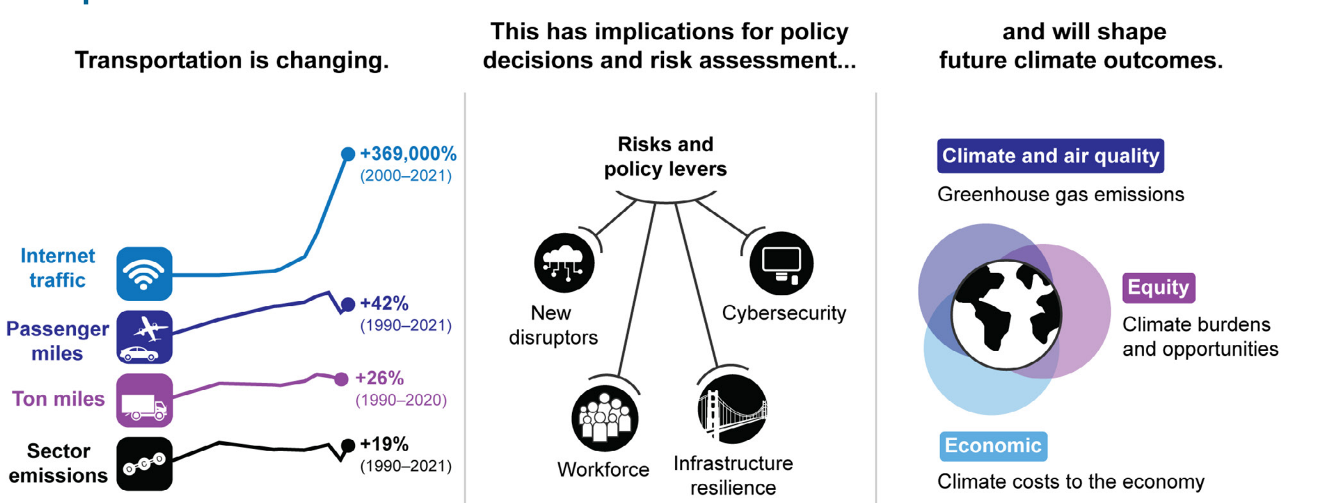
Key Message 13.2

Climate Change Combined with Other Disruptors Requires New Frameworks and Competencies

Climate action creates an opportunity to address concurrent disruptors, including cyber-technology integration, challenges with the condition of existing assets, and a changing workforce (*medium confidence*). Climate change has accelerated a transition to the use of more advanced approaches, including updated technologies, tools, and best practices (*high confidence*). Further recruitment and training of the sector's workforce is needed to effectively address these fundamental challenges (*high confidence*).

Moving toward a decarbonized, climate-adapted, and resilient transportation system can be more than simply a response to the climate crisis. The 21st-century transportation sector is undergoing rapid transformation. The integration of cyber-technology and advances in autonomous and connected vehicles are changing the nature of what transportation systems are and how they operate. Transportation's future is a complex, integrated, and dynamically shifting landscape marked by considerable uncertainty.[80] It faces unprecedented challenges from several sources: COVID-19; the growth of new technologies, business models, and opportunities; a massive shift to electrification; a changing logistics sector;[81,82] and significant workforce, diversity, and inclusion challenges. Cyber-vulnerabilities pose a profound challenge to the transportation industry[83,84,85] and communities, as well as national security risks. Figure 13.2 illustrates the complex relationship between the transportation sector, policy decisions and risk assessment, and future climate outcomes. Transportation system decisions made today have long-term implications for GHG emissions and climate adaptation. New tools and training have the potential to help navigate climate adaptation and disruption.

Transportation Futures

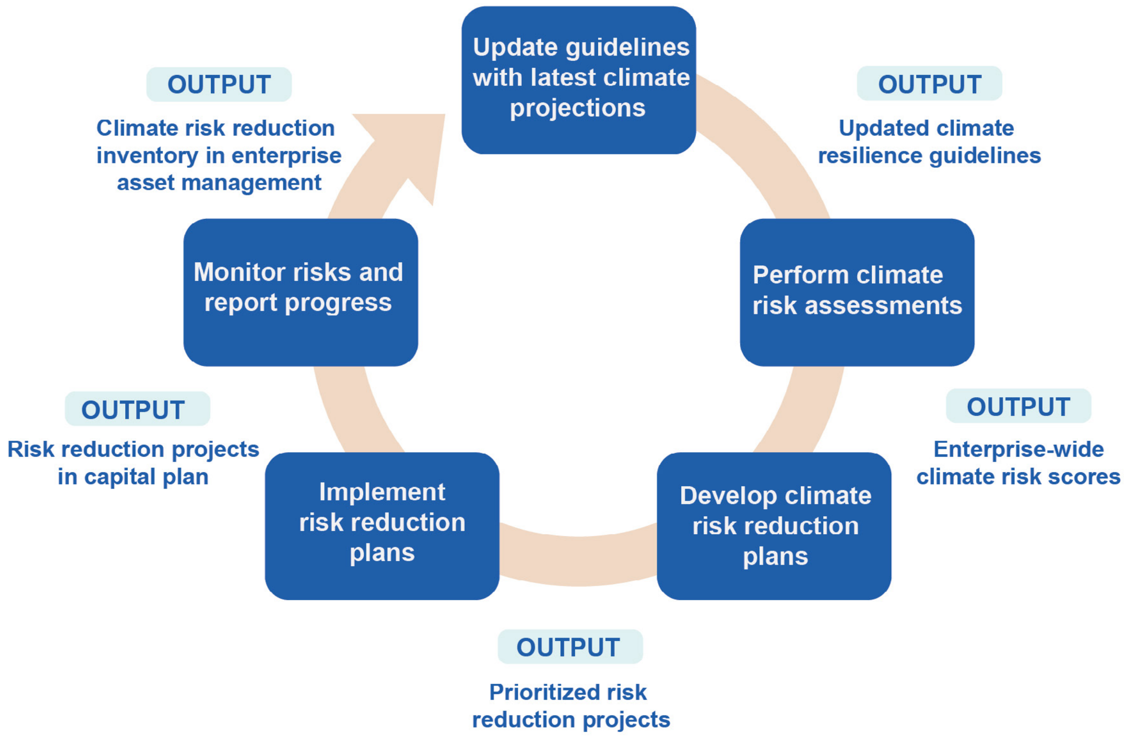


A shifting transportation landscape, and how we respond to it, will determine future climate outcomes.

Figure 13.2. The ways people, goods, and services travel have changed since 1990, especially with the dramatic rise of internet traffic. These changes create new challenges, such as cybersecurity impacts, and, coupled with workforce and infrastructure resilience challenges, are increasing the policy decisions in transportation. These decisions will shape future climate outcomes. Figure credit: Open Society Foundations, Introducing Youth to American Infrastructure Inc., NOAA NCEI, and CISESS NC.

Frameworks are emerging to help decision-makers incorporate climate uncertainty into infrastructure planning.[86] Using available data and tools provided by technological advancements in other sectors such as computing, sensors, cyber-technology, and statistics, public agencies and private companies are creating greater awareness and, in many cases, taking action to address the uncertainty brought about by climate change on the expected use and lifespan of transportation systems and on the design, construction, operations, and maintenance of transportation-related infrastructure (Figure 13.3).

Resilience Planning Cycle



Improving transportation resilience requires an iterative approach.

Figure 13.3. This concept demonstrates a potential iterative approach to planning, investing, and building for climate resilience in the transportation sector, starting with 1) integration of updated climate projections into guidelines and workflows and proceeding to 2) assessment of climate change–related risks, 3) prioritization of climate risk-mitigation investments and strategies, 4) implementation of prioritized strategies, and 5) ongoing tracking and reporting of progress, culminating with updates to enterprise asset management (EAM) data—the foundation for the next resilience cycle. This process is underpinned by a strong climate resilience policy. This approach is designed to ensure that the pursuit of resilience is ongoing, adaptable, and both immediately relevant and future focused. Figure credit: Port Authority of New York and New Jersey.

Integrating climate data into engineering science is an emerging practice.[26,87,88,89,90,91,92,93,94,95,96,97,98] Advances in tools used for the planning, design, and construction of transportation and infrastructure projects are further changing the state of the practice.[92,95,99,100,101,102,103] The results of multiple years of climate research are beginning to see their way into transportation capital programming and project execution. Adaptation planning is beginning to recognize the challenges and opportunities of concurrent disruptors. For example, by harnessing low-cost heat and air quality sensors and increasingly accessible communication networks, researchers are showing the capabilities of informing active mobility users of high-exposure locations.[104] Decision-makers faced with evacuating large groups of people from extreme events can consider EV or non-traditional fleets. There is an ongoing effort, for example, to use EVs for powering buildings during outages.[105,106] Sensors that can detect climate hazards such as flooding and communicate risks to the public, or that can be integrated into existing intelligent transportation systems, are rapidly advancing.[107]

Planning for adaptation concurrently with other disruptors will also require novel workforce capabilities. The transportation sector faces a number of workforce-related challenges, including aging, high retirement rates, retention issues, and industry-wide shortages for specific essential jobs; persistent underrepresentation of women and people of color; career awareness and image challenges impacting the attraction and recruitment of new employees; and significant technological impacts requiring further training and education related to the wider adoption of electric vehicles, information technology/cybersecurity risks, and increasing advances in artificial intelligence, robotics, and autonomous and connected vehicles.[108] As more employees gain the skills to navigate climate hazards, the sector will be better positioned to build resilience.[27,109,110,111] The transportation sector can define the competencies needed for its future workforce and collaborate with educational programs (including universities, professional societies, and continuing education programs) to modernize training. Elevating human resources management as an important element of organizational risk and vulnerability assessment will help ensure that workforce development and readiness are an integral part of climate mitigation and adaptation efforts (KMs 5.2, 7.3, 11.3, 16.2, 20.6; Ch. 29). The sector would further benefit from "K to gray"—a multipronged strategy that recognizes the importance of employee and workforce development and readiness at all levels and ages.[112]

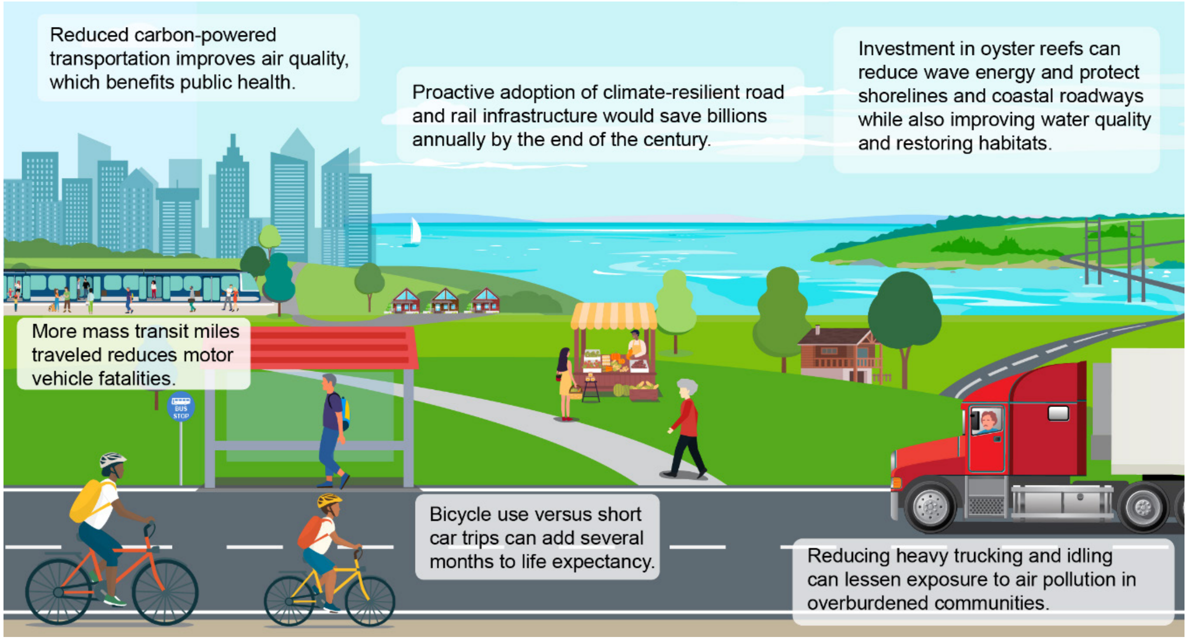
Key Message 13.3

Sustainable Transportation Would Produce Societal Benefits

A carbon-free, sustainable, and resilient transportation system would have co-benefits for human health, environmental justice, the natural environment, and economic development (*very high confidence*). When these co-benefits are considered, the benefits of greenhouse gas mitigation actions in the transportation sector far outweigh the costs (*high confidence*).

A carbon-free, sustainable, and resilient transportation system would have societal benefits beyond reduced climate change impacts, potentially leading to improvements in air quality, physical fitness, incidence of cardiovascular and respiratory disease, mental health, crash rates, noise pollution, social equity, ecosystems, biodiversity conservation, energy independence, and the economy.[113,114] When these co-benefits are considered, the benefits of GHG mitigation actions in the transportation sector far outweigh the costs (Figure 13.4).[115] Considering the impacts for different population subgroups can also ensure that these actions improve environmental, health, and social equity. These societal co-benefits would be particularly powerful in urban areas, where large numbers of people are experiencing elevated air pollution, health inequities, heat stress, traffic congestion, long commutes, and the negative health consequences of a sedentary lifestyle (Ch. 12). In contrast to the long-term and planetary-scale impacts of reducing GHGs from the transportation sector, these societal benefits would accrue immediately and locally, wherever the transportation emissions changes are implemented.

Co-benefits of Mitigation and Resilience



Decarbonizing transportation could save money and improve air quality, social equity, and the health of people and ecosystems.

Figure 13.4. Integrating mitigation and resilience into transportation policies and planning at multiple scales leads to improved air quality, enhanced physical fitness from cycling, reduced environmental injustice as a result of decreases in heavy-duty trucking and idling, healthier ecosystems, and more economic opportunities. Figure credit: George Washington University and Jacobs.

The benefits of infrastructure and transportation resilience are also well documented and include increased reliability; lower costs to travelers, industry, and consumers, as well as to owners and operators of transportation infrastructure; improved safety and better health outcomes for workers and travelers; and the ability to support evacuations (KM 22.3).[116,117,118,119,120] However, significant resources are necessary to ensure the continued benefits and state of good repair of sustainable and climate-resilient transportation systems for all communities.[102]

Reducing GHGs in the transportation sector would also achieve co-benefits from improvements in air quality, climate and environmental equity, and physical fitness, as well as reduced incidence of cardiovascular disease, diabetes, and cancer (Figure 13.4; KM 12.3; Chs. 14, 24, 32)—all of which could counteract some climate impacts on human health (Ch. 15). Given the significantly high economic cost of air pollution in the United States, the monetary value of these benefits would be substantial.[121] Traffic-related emissions are a significant contributor to air pollutants, particularly fine particles ($PM_{2.5}$), ozone (O_3), and nitrogen dioxide (NO_2), all of which are associated with higher rates of illness and death.[122,123,124,125,126] In addition, emerging evidence suggests that exposure to elevated CO_2 levels indoors impacts cognitive function.[127] Reducing outdoor CO_2 emissions from the transportation sector could also reduce indoor CO_2 levels.[128]

Fuel efficiency, more stringent vehicle emissions standards, reduced passenger vehicle traffic, vehicle electrification, and mode switching to public transportation and walking or biking would result in co-benefits from improved air quality and better health. Modeling studies show that vehicle electrification reduces mortality related to $PM_{2.5}$ and O_3, even when considering increased emissions from additional energy demand.[129] However, increased energy use from demand for electricity, lithium mining, and potentially heavier vehicles can offset some of these air quality improvements when electricity generation is from burning fossil fuels, highlighting the importance of transitioning to non-combustion electricity generation, such as from renewable energy sources (KM 13.4; Ch. 12).

COVID-19 lockdowns provided an unprecedented opportunity to examine how reduced passenger vehicle activity (and increased telework and bike use) affected CO_2 and air pollution. CO_2 emissions dropped by about 32% in April 2020 but rebounded to near normal by 2021, indicating that lifestyle changes (such as those experienced during the pandemic) must be coupled with transformative changes in transportation systems to reach GHG emissions-reduction targets (Focus on COVID-19 and Climate Change). In terms of air pollution, many cities experienced dramatic reductions in NO_2 pollution,[130,131] although impacts on $PM_{2.5}$ and O_3 were much more variable and location dependent.[132] Because traffic-related air pollution is inequitably distributed within US cities,[131,133] moving toward a carbon-free transportation system would also advance environmental and health equity. For example, air pollution inequity would be reduced through vehicle electrification, improved fuel efficiency, and structural actions to reduce vehicle-miles traveled for moving people and goods, such as changing the design of cities and increasing reliance on emissions-lowering modes, increasing public transportation use, and moving freight by rail rather than by road (Ch. 12). Walking or cycling instead of driving improves physical fitness and overall health,[115,134,135,136] and steps could be taken to ensure that safe access to these active transportation modes is available equitably across social groups. Active transportation and more time in natural environments also have mental health benefits, including improved cognitive function and well-being.[137] Reduced vehicle traffic also leads to fewer crashes and injuries.[115]

In recent years, several decision support tools have been developed to quantify and value the multiple benefits of actions that reduce transportation GHG emissions, including the Integrated Transport and Health Impact Model[138] and the Health Economic Assessment Tool for walking and cycling.[139] Integrating co-benefits into transportation policies and planning at multiple scales (e.g., neighborhood, urban, national) can create additional appeal for reducing transportation-sector GHG emissions for both decision-makers and the public. Key Messages 13.1 and 13.2 provide context on how to consider uncertainties in these decisions.

Key Message 13.4

Equitable Distribution of Transportation Trade-Offs and Benefits Requires Community Involvement

Although implementing adaptation and mitigation measures in the transportation sector will produce essential benefits and co-benefits, including addressing existing inequities, additional consideration is needed to avoid or reduce potential adverse consequences associated with these measures (*high confidence*). Moving toward climate resilience and environmental justice requires that these considerations, as well as current and historic inequities, be assessed through transparent and inclusive processes in order to provide equitable protection from environmental and health hazards and equitable access to transportation benefits (high confidence).

The need for climate mitigation and adaptation has created an opportunity to rethink transportation systems and land use at all levels. Still, such transformations (or decisions to maintain the status quo) may include some risks, with benefits sometimes accompanied by adverse or uncertain impacts (KM 13.2; Ch. 12). Political and policy actions in the US are generally based on compromise among an array of interests, which may lead to trade-offs that fall short of idealized climate mitigation or adaptation actions. Moving toward equitable climate resilience and environmental justice via a just transition requires that consideration of such trade-offs be addressed through the full participation of relevant communities (Chs. 16, 31; KM 22.3).[140] Environmental justice also requires that trade-offs be managed in ways that address community self-determination,[141,142] as well as the needs of communities that are affected by transportation infrastructure and the impacts of the existing built environment or that currently lack reliable, sustainable, and affordable transportation services (Figure 13.5; Chs. 11, 17).[106,143,144]

Adopting alternative energy sources to reduce transportation emissions from fossil fuels has enormous potential for direct GHG and air pollution reduction, as well as opportunities for a just transition, but also includes potential risks or trade-offs. For example, battery production for EVs is mineral-intensive, requiring large quantities of lithium, nickel, copper, tantalum, and other minerals. Mining these raw materials may result in environmental degradation, public health harms, or displacement of nearby communities, as well as cultural impacts, including loss of sacred spaces.[145,146] Potential risks associated with adopting alternative energy sources should be considered in the context of current trade-offs related to existing energy sources, including the well-documented environmental and global climate change effects and adverse human health impacts resulting from the use of internal combustion–engine vehicles and fossil-energy power plants (KMs 5.2, 12.2). The siting of power-generation facilities, including utility-scale renewables, can have similar impacts. Experts have also noted that used batteries and electronic components pose the problem—and the opportunity—of repurposing, recycling, and disposal,[147] which researchers are currently working to address. Vehicle power source changes can also affect the distribution of road-user fees;[148] preferential registration fees are designed to signal preferences for one power source over another. Both of these revenue strategies could entail transportation funding trade-offs. The transition to zero-emissions vehicles may result in only localized air pollution reductions (KMs 13.3, 14.5).[149,150]

Considerations of Equitable Climate Adaptation and GHG Mitigation from Transportation Systems

Reducing emissions involves trade-offs that have implications for reliability, equity, and environmental quality.

Figure 13.5. This figure shows many of the considerations where risks may arise as changes are made to transportation systems. Each tab on the figure represents a potential trade-off to all of the other factors shown. For example, changing transportation fuels or moving to electric drivetrains can decrease greenhouse gas and air pollutant emissions but may also affect transportation availability (which includes both geographical location and affordability) and reliability in underserved communities or in communities adapting to changing climates. Further, mining of raw materials for those technologies has the potential to damage ecosystems and cultural or sacred landscapes. Accordingly, decisions about climate mitigation and adaptation in transportation systems should be carefully considered through lenses of environmental justice and community self-determination. Figure credit: EPA and University of Idaho.

Climate adaptation actions entail consideration of trade-offs. For example, moving a coastal roadway inland to avoid sea level rise (i.e., managed retreat) may not allow for an immediate modal shift, but it may provide an opportunity to reconsider the size and capacity of the roadway and also allow for landscape restoration along the original alignment, as illustrated by the Highway A1A Redesign Project in Fort Lauderdale, Florida, and the Piedras Blancas Highway 1 Realignment project in San Luis Obispo, California (Ch. 9).[151,152]

For the freight transportation system, equitable distribution of trade-offs under a climate change framework will also require particular attention. In addition to turning over vehicles and equipment to lower-emissions or zero-emissions technologies, there are opportunities to obtain energy savings and emissions reductions by shifting freight from road transport to rail or water. Further infrastructure development will be necessary to make such mode shifting more viable.

Changing the geographical footprint of freight systems also brings up trade-offs. Inland port facilities can receive and manage cargo that has been unloaded from a seaport some distance away and transported via low-polluting transport modes (in terms of tailpipe and full-life-cycle air pollutant and GHG emissions, such as electric or hybrid locomotives or trucks) or highly efficient modes (energy use per cargo per mile, such as rail), or both, with the potential to boost system efficiency and reduce air pollutants and GHG emissions and reduce exposure to air pollutants in communities near seaports.[153] However, people living near such inland freight facilities could in turn experience increased traffic, air pollution, and environmental damage, creating or exacerbating environmental injustice. Emissions inventory methodologies can help to quantify these impacts and enable affected communities and decision-makers to develop emissions-reduction strategies from different activities and/or equipment types (Focus on Risks to Supply Chains).[154,155]

Trade-offs related to the freight workforce are also becoming clear. For example, independent truck owner-operators, who do not work for a larger employer and own their own trucks, may not have the resources to purchase and operate cleaner vehicles or have access to appropriate fueling or charging infrastructure.[156,157]

Traceable Accounts

Process Description

Selection of the author team considered a balance in gender, race, geography, and affiliation type. In addition, a holistic systems approach was considered essential in the development of this chapter. While transportation is the primary source of greenhouse gases and air pollution, there is a recognition that mitigating climate change impacts and developing transportation adaptation strategies have vital implications for other sectors. For these reasons, the authors were also selected for their expertise in the built environment and infrastructure, workforce development, education, funding and financing, public health, safety and security, customer experience, diversity and inclusion, and downscaled data analysis, as well as knowledge of global systems and resources. Special consideration was given to authors' understanding of perspectives from rural, urban poor, Arctic, and Pacific Islander communities; youth; and the Global South.

The author team was scheduled to meet every Wednesday throughout the Fifth National Climate Assessment (NCA5) process. During those meetings, the chapter lead (CL) facilitated meetings by going through the outcomes and milestones expected at every phase of the project, mitigated any specific process concerns, invited guest speakers such as Technical Support Unit (TSU) staff and technical contributors as necessary, and developed and followed up on milestones and expected outcomes. On certain weeks, meetings were not held, either to make time to complete specific tasks or for author team members to consult with TSU staff, or when a milestone or deliverable needed to be appraised within the chapter team or with other chapters teams. These weekly team meetings were also opportunities to build a consensus.

The author team was given subsections to work on and develop, but each subsection team member was free to work on or collaborate, as appropriate, with other subsection teams.

The CL and federal coordinating lead author (CLA) met with leadership from other chapters, taking note of their Key Messages (KMs). The CL provided an overview of these KMs to the Transportation chapter author team to help shape the development of each KM and its supporting narrative, figures, and tables (where appropriate). The CLA confirmed with CLAs from other chapters where statements made in the Transportation chapter could be reinforced by the assessments made by other chapters and vice versa.

The author team conducted a public meeting in February 2022, after the Zero Order Draft was submitted, with two plenaries and three breakout sessions. Input was received from the general public at these meetings. Additional stakeholder engagement was held for youth interested in participating in the NCA5 process. Transportation and other chapters made a presentation and joined breakout rooms where questions were answered. Additional comments on the Third Order Draft were received from the public and from the National Academies of Sciences, Engineering, and Medicine (NASEM).

These public and NASEM comments were assigned individually to chapter authors who could best provide a draft response. Draft responses were reviewed by the author team and finalized on consensus. The chapter's review editor provided feedback on these responses, and a final response was adopted. The chapter was revised according to the final responses to the public and NASEM comments.

Key Message 13.1

Limiting Transportation Sector Emissions and Integrating Climate Projections Can Reduce Risks

Description of Evidence Base

There is significant and increasing evidence of the greenhouse gas (GHG) emissions from the transportation sector and how those emissions could change into the future. EPA's Inventory of US Greenhouse Gas Emissions and Sinks provides a year-by-year estimate of GHG emissions from the transportation sector.[1] Scenarios describing changes in transportation sector emissions into the future differ based on assumptions about technology, powertrain, demand, and other variables.[1,2,3,5,6] The literature often focuses on identifying a confluence of variables needed to meet GHG-reduction goals. Electric vehicle (EV) adoption, including the GHG intensity of charging, and fuel cell vehicle development have become rich areas of study.[7] The costs of decarbonizing heavy-duty vehicles are dropping, but increases in truck-miles could offset benefits.[18,19] Aviation forecasts often contrast fuel economy gains relative to changes in demand.[17]

Literature and evidence on the impacts of climate hazards on transportation infrastructures and operations are growing rapidly. The literature generally covers either the vulnerabilities of systems or the costs of adaptation.[23,40] Costs to implement adaptation and mitigation vary across the country and according to the scale of actions, are inconsistently tracked over the lifetime of a policy or program, and tend to be tracked only in each phase of the initiative. There is also a growing body of risk, vulnerability, and resilience frameworks for transportation systems, and no clear consensus has emerged on the precise steps needed to protect transportation systems against climate hazard–associated uncertainty.[61]

With respect to incorporating observed and projected changes in climate into the design criteria of infrastructure systems, there is a small but growing evidence base. Although applicable to transportation infrastructure, the majority of the work in this space relates to infrastructure more generally.

Major Uncertainties and Research Gaps

The long-term outlook and extrapolation of trends in transportation GHG emissions, especially given supply chain shocks resulting from COVID-19, are highly uncertain.[15,16] While EV market shares are growing, they still represent a small fraction of the light-duty fleet and an even smaller fraction of the heavy-duty fleet.[7] How EV adoption and fuel cell vehicle development and adoption, in combination with other factors, result in future GHG emissions changes in the transportation sector is highly uncertain.

There is also uncertainty regarding whether and how incorporating new data, improved data, and climate projections into transportation sector decision-making leads to improved outcomes. Uncertain localized climate data, uncertainty in future climate, and uncertainty in applying legacy risk-based approaches under new climate paradigms result in an unclear picture of how new and enhanced data with new resilience frameworks translate into better decision-making.[40]

Description of Confidence and Likelihood

There is *very high confidence* that the transportation sector is the most significant single-sector contributor to national greenhouse gas emissions. This is corroborated by extensively reviewed, studied, and verified data on vehicle travel and associated emissions. There is also *very high confidence* that the transportation sector faces increasing risk from climate-related extreme weather. Transportation systems are diverse and present everywhere in the US, meaning that they are exposed to all climate hazards. Aging assets and state-of-good-repair challenges contribute to this risk. There is *very high confidence* that transportation agencies and planning organizations understand potential climate impacts and are addressing them to varying degrees by incorporating climate projections into planning, design, operations, and maintenance to reduce risks to the sector. Peer-reviewed articles and publicly available reports and documents support the stated confidence levels.

Specific to vulnerabilities and impacts, the author team recognizes that agencies may not release operational data and that, therefore, this information may not be publicly available, except in cases where such information would be useful to support gray literature. Those references were called out with a full understanding that data and statistics may have been reported without the full context of the source of the empirical information.

Key Message 13.2

Climate Change Combined with Other Disruptors Requires New Frameworks and Competencies

Description of Evidence Base

This assessment is based on publicly available sources, including federal and state information; discussions with diverse subject-matter experts and technical contributors; and a focused literature scan, including some peer-reviewed sources. Although peer-reviewed literature broadly supports the notion that the transportation sector faces a variety of emerging, potentially disruptive changes,[80] few peer-reviewed sources exist that explicitly link coordination of those challenges (and solutions) to climate action. The acceleration of climate change–informed decision-making in the transportation sector is best demonstrated by the recent proliferation of frameworks and tools for this purpose,[27,86] but peer-reviewed literature also supports this claim.[99] Ample peer-reviewed and gray literature supports the discussion of emerging transportation workforce challenges[112] and the corresponding need to upskill and diversify the demographics of transportation workers to address these challenges.

Major Uncertainties and Research Gaps

Key Message 13.2 focuses on potential opportunities and threats stemming from the convergence of a changing climate, emerging non-climate disruptors, and rapid, concurrent transformation of the transportation sector and its workforce—all of which compound uncertainty. In particular, the rate of adoption of EVs and the maturity and deployment of autonomous and connected vehicle technologies are moderately to highly uncertain. In addition, the transportation sector is not monolithic, potentially reducing the credibility of overarching claims or conclusions. Major differences exist across the widely varying transportation modes and regions of the United States, including notable divergences between urban, suburban, and rural environments; areas of relative wealth or poverty; and historically underrepresented and/or overburdened communities.

Notable research gaps include a relative lack of publicly available data of sufficient uniformity, granularity, and credibility (especially from subsectors dominated by private operators or where agency operational data are not publicly available), which complicates attempts to achieve data-informed decisions and monitor outcomes. Relatedly, there is currently little consensus on how sustainability and resilience, as well as climate change goals, progress, and outcomes, are reported in the sector.

Finally, peer-reviewed literature on the potential co-benefits (or disbenefits) of coordinating responses to climate-related challenges and non-climate disruptors is relatively scant, despite ample anecdotal evidence.

Description of Confidence and Likelihood

Due to the lack of a strong foundation of peer-reviewed literature, the claim that climate action presents an opportunity to address emerging non-climate disruptors is assigned *medium confidence*, primarily rooted in gray literature and credible expert opinion. The well-documented, relatively recent proliferation of resources to support deliberate climate action in the sector yields a *high confidence* rating for the claim that approaches and tools are available and are being applied, with the caveat that little evidence exists that these tools produce actionable outputs or successful outcomes. There is *high confidence* that further recruitment and training is needed to ensure that the sector's workforce can succeed amid rapid climate and non-climate transformations. Sufficient data to support likelihood assessments are not readily available.

Key Message 13.3

Sustainable Transportation Would Produce Societal Benefits

Description of Evidence Base

This assessment is based on peer-reviewed journal articles and publicly available reports that evaluate multiple impacts of actions taken in the transportation sector to mitigate carbon emissions and become more resilient to the effects of climate change. The evidence base for co-benefits comes from studies focusing on both the societal burden from the current transportation system and the societal benefits that would come from a less carbon-intensive and more climate-resilient transportation system. This evidence base covers transportation impacts on health via motor vehicle crashes, high air pollution and noise levels, heat island effects, and lack of green space and physical activity.[114] It also covers how transportation provides many jobs, which generate income and improve health.[114] These studies are multidisciplinary and vary in methods, including both quantitative and qualitative approaches.

Among the most studied consequences of our current transportation system are air quality and health impacts. A large body of literature developed over decades demonstrates that vehicle emissions contribute to poor air quality and a range of deleterious health outcomes, including premature mortality, cardiovascular disease, respiratory disease, and lung cancer.[122,123,126] Studies have also shown that policies that reduced emissions from the transportation sector, including through transitioning to zero-emissions vehicles, can reduce the incidence[124] and exacerbation of asthma.[125] Additional studies have explored potential air quality and health benefits of hypothetical policies, accounting for both reduced tailpipe air pollution emissions and potentially increased emissions from fossil fuel–based electricity generation.[129]

While fewer studies focus on the other pathways of improvements that would come from different actions that could be taken to decarbonize and improve resilience of the transportation system, a growing body of literature assesses benefits for physical fitness,[134,135] reduced crashes and injuries,[115] improved health for transportation workers,[117] and environmental justice and health equity.[131] Fewer studies have taken a holistic view of many societal benefits that would accrue simultaneously, which is necessary to comprehensively evaluate different actions that could be taken, from tailpipe emission and fuel efficiency standards to restructuring the transportation system in cities to encourage public transportation and walking and cycling. However, studies find that these potential co-benefits can motivate public, private, and financial actions to mitigate greenhouse gases[113] and can outweigh the costs of taking action.[115]

Major Uncertainties and Research Gaps

Co-benefits assessments are often highly context-specific, limiting the ability to extrapolate the results to different geographical areas, populations, and actions, including policies, programs, and projects. Costs to implement adaptation and mitigation vary across the country and are often tracked only in individual phases of the initiative. There is a lack of research verifying the actual costs and benefits of programs and projects that have already been implemented to reduce transportation-related carbon emissions and improve the resilience of the transportation system. Some national calculators perform such cost–benefit analysis. These include the Integrated Transport and Health Impact Model[138] and the Health Economic Assessment Tool for walking and cycling.[139] However, there is still a gap in the consistency of the true meaning of the quantified outcomes relative to the transportation sector, the area where those programs or projects are created, and how those outcomes could be integrated for an accurate measure of benefits beyond project-level co-benefits. An important gap lies in more holistic life-cycle tracking of the costs over the life of the asset or program.

There is also a lack of research that assesses the distributional benefits of transportation mitigation and resilience policies, programs, and projects on different population subgroups and overburdened communities. For example, studies find that transportation tailpipe emissions contribute to racial and socio-economic disparities in air pollution levels; however, several key technical limitations make it challenging to fully characterize which communities could experience the greatest improvements in air quality and associated health benefits from national, state, and local policies or other measures that reduce transportation tailpipe emissions. Similarly, there is a need to consider the effectiveness of different mitigation and adaptation actions for different locations and populations, given inequities in safe, accessible, and reliable transportation options.

Description of Confidence and Likelihood

There is *very high confidence* that policies, programs, and projects to reduce transportation-related carbon emissions and transition to a more resilient transportation system would lead to environmental, health, and economic co-benefits. This conclusion is based on the strength and consistency of the peer-reviewed literature and publicly available reports documenting the many societal improvements that would come from actions to decarbonize the transportation sector and make it more resilient to climate change. Despite the research gaps limiting our understanding of the co-benefits of specific mitigation and adaptation actions taken in specific locations and of the impacts of these actions on environmental, health, and social equity, the large and multidisciplinary body of literature finding that mitigation and improved resilience results in many societal co-benefits provides sufficient evidence to draw this conclusion.

There is *high confidence* that when these co-benefits are considered, the benefits of GHG mitigation actions in the transportation sector far outweigh the costs. Some evidence suggests that potential co-benefits outweigh the costs of taking action, particularly when the action results in reduced human mortality. However, the value of co-benefits and costs are highly context-specific and dependent on the type, scale, and design of the action being considered or taken.

Key Message 13.4

Equitable Distribution of Transportation Trade-Offs and Benefits Requires Community Involvement

Description of Evidence Base

This assessment is based on peer-reviewed journal articles and government reports. The environmental and societal impacts of various transportation technologies and systems are well documented.[146] Sources and specific locations of raw materials for electrified transportation technologies are also well known, and the environmental and community impacts of mining and extraction operations have been deeply analyzed in many specific locations.[145] The trade-offs of climate change mitigation and adaptation in the freight transportation sector are also well known, as governments, freight operators, and cargo owners are concurrently implementing and analyzing actions in those areas, and planning for the future, with extensive documentation of those processes.[153] The benefits of community engagement in government processes, including in the transportation sector, are also extensively documented in the literature.[140] There is also an emerging best practice to include equity and inclusion criteria in the development and implementation of transportation strategies.[143,144]

Major Uncertainties and Research Gaps

Projections of the specific life-cycle environmental and societal impacts of not-yet-implemented transportation technologies and systems are necessarily uncertain. Specifically, impacts of mineral mining for EV battery raw materials have been extensively analyzed for sites within the lithium triangle of South America; however, large-scale mining of such materials is less prevalent in the US, so fewer analyses of these impacts have been performed.[145] There is also a lack of research analyzing the environmental and GHG benefits from freight transportation mode shifts.

Description of Confidence and Likelihood

There is *high confidence* that significant trade-offs will occur in implementing adaptation and mitigation measures in the transportation sector, based on the strength and consistency of the peer-reviewed literature and publicly available reports regarding contemporary environmental and energy transitions. There is *high confidence* that environmental justice requires transparent and inclusive processes, as the literature and government policy[141] clearly indicate that equal access to decision-making processes is a key element of environmental justice.

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