

Cross-Sectoral Economic Impact Analysis of Climate Change in New York State

Chapter 8: Transportation Sector

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Cross-Sectoral Economic Impact Analysis of Climate Change in New York State

Chapter 8: Transportation Sector

Final Report

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Abstract

Transportation infrastructure in New York State includes roads, rail systems, ports, air transport, bridges, and subways, all of which are vulnerable to the impacts of climate change, such as high heat and heavy precipitation. For this sector, we modeled and quantified the economic impacts associated with the effects of temperature, precipitation, flooding, and changes in freeze–thaw cycles on roads, the effects of extreme heat events on rail system performance, and high-tide flooding on coastal roads. Other potential impacts are discussed qualitatively but were not able to be modeled for this study, including the impacts of sea-level rise and storms on ports and small harbors, flooding, storms, and rising temperatures on air transportation, changes in precipitation, storms, and sea level on bridges, and sea-level rise, storms, and changing temperatures and precipitation on subway systems. The analysis shows that proactive, forward-looking adaptation that incorporates future climate conditions can significantly reduce the economic impacts in this sector. As with all modeling, this work could not capture every aspect of the transportation sector, and there are data and modeling limitations that are inherent in any analysis like this.

Keywords

climate change, impacts, economics, economic impacts, projections, scenarios, adaptation, socioeconomic, transportation, infrastructure, roads, rail, railroads, coastal

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Acronyms and Abbreviations

°F	degrees Fahrenheit
ASCE	American Society of Civil Engineers
CMIP	Coupled Model Intercomparison Project
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
GCM	global climate model
GDP	gross domestic product
GHG	greenhouse gas
HTF	high-tide flooding
IRI	International Roughness Index
JFK	John F. Kennedy International Airport
lb	pound
LGA	LaGuardia Airport
m	meter
MTA	Metropolitan Transportation Authority
NCHRP	National Cooperative Highway Research Program
NOAA	National Oceanic and Atmospheric Administration
NOAA	National Oceanic and Atmospheric Administration
NYSERDA	New York State Energy Research and Development Authority
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway
USCG	U.S. Coast Guard
VOC	volatile organic compound

Report Summary

This chapter is part of a report that projects the economic impacts of climate change in New York State across eight sectors through 2100 under multiple climate, socioeconomic, and adaptation scenarios. The research team identified and applied existing literature and models to quantify or qualitatively assess climate-related impact categories, using standardized climate and socioeconomic inputs. The analysis used downscaled Coupled Model Intercomparison Project Phase 6 (CMIP6) climate data and gross domestic product (GDP)/population projections to estimate sector-specific impacts under Shared Socioeconomic Pathway (SSP)2-4.5 and SSP5-8.5 emissions scenarios. While the estimates reflect current best practices and modeling capabilities, limitations such as data availability, missing feedback loops, and gaps in demographic sensitivity likely lead to underestimation of total impacts.

Transportation Sector Chapter Insights

The following is a summary of findings for climate economic impacts in the transportation sector that are detailed in this chapter:

- The quantified economic impacts of climate change from the transportation sector total \$4.5 billion to \$10.4 billion annually by the end of the twenty-first century.
- Proactive adaptation in the roads subsector has the potential to significantly reduce damages, with a reduction of \$2.8 billion annually in the late century.
- The impacts of climate change on ports, air transport, and bridges are expected to add substantially to the total impact, although they are not quantified in this analysis.
- Impacts to rail systems account for 48% of total transport impacts in the near century.
- Coastal flooding impacts increase by 15 to 20 times from the near century to the late century under Shared Socioeconomic Pathways (SSP) 2-45 and SSP5-85, respectively.

1 Introduction

Transportation infrastructure, including roads, properties, and other assets, are vulnerable to effects from changing temperatures, precipitation patterns, and sea levels. The transportation sector literature related to climate change is characterized by many studies that incorporate investments in adaptation and consider multiple adaptation scenarios. Adaptation is shown to be cost effective for the transportation infrastructure sector, and avoidance through up-front investment reduces overall costs and impacts.

In this chapter, quantified impacts of climate change on the transportation sector include the effects of temperature, precipitation, flooding, and changes in freeze–thaw cycles on roads; the effects of high-heat events on rail system performance; and the impacts of high-tide flooding on coastal roads. The quantified economic impacts across these three subsectors are among the largest for the sectors considered in this study, second only to extreme-temperature mortality impacts in the health and human safety sector. The quantitative impact estimates incorporate the study-wide population and gross domestic product (GDP) projection assumptions as a key driver of future traffic volume on roads and rails, but do not incorporate the potential for future changes in modality of transport (e.g., whether current automobile drivers and passengers may switch to another transport mode or limit traveling or commuting overall). Additional transportation sector impacts that are partially quantified or addressed qualitatively include those on ports and small harbors, air transport, bridges, and subways. Table 8-1 summarizes the sector impacts assessed in this chapter.

This analysis includes some quantification of adaptation measures for the economic impacts of this sector for two scenarios: reactive response and proactive adaptation. For this study, the reactive response scenario assumes that responses and associated costs increase as impacts and damages increase, while practices stay the same and continue to assume a historical climate rather than incorporating future climate change (Table 8-2). Proactive adaptation includes measures that incorporate future climate change. See Chapter 2, Agriculture Sector, for more information on the response and adaptation scenarios considered in this study.

Table 8-1. Annual Statewide Economic Impacts to Transportation Categories

Values represent total statewide impacts relative to the baseline by shared socioeconomic pathway (SSP), under a reactive response scenario, reported in millions of 2021 U.S. dollars (USD).

Category	Near Century (2030s)		Midcentury (2050s)		Late Century (2080s)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Roads, Reactive Response	\$373	\$424	\$952	\$1,357	\$1,369	\$2,974
Roads, Proactive Adaptation	\$174	\$166	\$158	\$258	\$109	\$142
Rail, Reactive Response	\$500	\$586	\$753	\$1,179	\$480	\$3,335
Rail, Proactive Adaptation	\$6	\$7	\$21	\$28	\$68	\$123
Coastal Roads, Reactive Response	\$180	\$200	\$510	\$640	\$2,600	\$4,000
Coastal Roads, Proactive Adaptation	\$41	\$49	\$24	\$28	\$18	\$31
Ports and Small Harbors	Ports are particularly susceptible to climate-driven flooding and storm damage because they are located directly on coastlines. Economic impacts are not quantified by this analysis but may exceed \$1 billion annually.					
Air Transport	Air transport infrastructure is vulnerable to most primary climate stressors, with potentially significant impacts expected due to extreme weather and temperature-related impacts that could result in delays and cancellations. Economic impacts could exceed \$100 million annually.					
Bridges	Increased occurrence of high streamflow events and other extreme weather associated with climate change will increase the probability of bridge damage or failure, resulting in significant repair and delay costs that could exceed \$500 million annually.					
Subways	Subway systems are mainly susceptible to damage and disruptions from flooding as sea levels rise and severe storms increase in frequency and intensity. Reliance on the electric grid creates additional vulnerabilities due to increased demand during heat waves.					

Table 8-2. Summary of Response Assumptions for the Transportation Sector

Category	Reactive Response Assumptions	Proactive Adaptation
Roads	• Roads are repaired as climate-induced temperature and precipitation extremes cause damage. • Traffic delays result from the need for unplanned repair actions.	• Roads are repaired but also upgraded for optimal resilience anticipating future climate changes. • Upgrades are planned in advance to minimize traffic delays and the need for future repairs.
Rail	• Train speeds are reduced as extreme temperatures present hazards to rail safety, leading to passenger and freight rail delays.	• Rail temperature sensors are installed and used to optimize the use of train speed controls in response to temperature hazards, in turn minimizing passenger and freight rail delays.
Coastal Roads	• Drivers adjust their routes in response to sunny day flooding (also known as high-tide flooding) risks, within the limits of existing local road alternatives. • Cost-effective flood protections installed to protect properties provide ancillary protection for some nearby roads.	• Includes all reactive actions, plus additional cost-effective road-raising and/or road flood protection actions are implemented.

Note that other chapters of this report discuss additional related infrastructure damages, such as electricity infrastructure and particularly the market penetration of electric vehicles in response to State decarbonization and electrification policies (energy) and structure damage from coastal and inland flooding (buildings).

1.1 Related Impacts: Connections across Sectors

This section highlights related impacts and connections across other sectors.

- **Society and economy:** Increased construction activity causes traffic delays, which impact passengers' travel time and the transportation of goods. Further, people who Commute may experience delays that result in lost wages. workers may also experience delays or be unable to get to work during rail closures, leading to lost productivity and wages.
- **Energy:** New York State's decarbonization and electrification efforts are expected to have substantial effects on vehicle types (transitioning to electric vehicles). These effects are evaluated in Chapter 5, Energy Sector, in terms of their impact on the total cost of electric supply and associated mobile infrastructure. This Transportation sector chapter focuses only on fixed road and rail assets and their vulnerability to climate change.
- **Ecosystem services:** Where roadways are located near river valleys, soil erosion along river channels can threaten the integrity of roads and require protections and repairs.

2 Quantitative Damages

This section discusses the quantitative analyses performed for this sector.

2.1 Roads

The scope of economic impacts considered includes costs to repair roadway infrastructure damage and traffic-delay costs, which are associated with heat stress and precipitation events.

Temperature changes and increased precipitation events due to climate change can damage roadways throughout New York State. The impacts result from increased rutting, cracks, and surface roughness after high heat and extreme precipitation events. This leads to a need for road repair or, if repairs are not completed, a reduction in vehicle speed to navigate damaged roadways and increased vehicle operating costs (VOCs) from driving on them.

Rut depth increases over the life span of the road, but it may increase faster due to temperature changes associated with climate change (Qiao et al. 2013). Additionally, in extreme heat and precipitation conditions, the flexible pavement that makes up the modern road system can expand and crack. Rutting, cracks, and general deterioration contribute to higher International Roughness Index (IRI) values, which measures how rough or smooth a surface is. Roads with high IRI may require frequent repairs, cause high VOCs for drivers (e.g., the need for more frequent vehicle repair, increased fuel costs, and external social costs associated with higher vehicle air pollutant emissions) and more delays due to repair schedules and speed reductions.

This analysis estimates the economic impact of temperature changes and precipitation events based on two previous studies: Neumann et al. (2021) and the U.S. Environmental Protection Agency (EPA 2017), which assess the effects of climate hazards on roadway infrastructure. The estimated costs include:

1. Expenses related to repair activities occurring when a climate stressor causes damage to infrastructure (accruing to entities responsible for road maintenance and repair)
2. Delays associated with speed reductions (accruing to road users, including both passenger and freight travel)

2.1.1 Methodology

This road analysis uses a consistent analytic framework to evaluate impacts of climate change under two alternative infrastructure management scenarios: reactive response and proactive adaptation. Quantifying the impact of increased climate stress on roadways under each scenario incorporates two components:

1. Estimating potential increases in repairs due to climate change-related damage
2. Estimating potential increases in delays and VOCs

Appendix B and Neumann et al. (2021) provide details of the scenarios, where “damage” refers to the physical manifestation of climate effects, and “cost” refers to the economic implications of either repairing the damage or, in the case of user and indirect costs, of not repairing it.

This analysis uses national average construction delay times from RSMeans (Gordian 2017) to estimate traffic delays from the time required to complete the climate hazard-induced road maintenance. We accounted for the potential for vehicles to avoid the damaged roads or the road maintenance by rerouting through an index that represents redundancy in the road network.

To quantify delay costs for passenger vehicle travel, we applied the value of travel time savings estimates from the U.S. Department of Transportation (DOT 2016). For freight vehicle travel, we used data from the National Cooperative Highway Research Program (NCHRP) *Truck Freight Reliability Valuation Model* (Hirschman et al. 2016).¹

¹ We modeled a third scenario, no adaptation, but is not included in the analysis due to its low likelihood. This scenario reflects repair and delay costs, but the repair cost component is limited by an estimate of historical spending for the period 1986–2005. If the need for repair associated with climatic stressors exceeds the modeled historical budget, and needed repairs are therefore foregone, there remains potential for continued damage to roads and losses to road users. The magnitude of costs for no adaptation are substantially higher than for the other adaptation scenarios, providing strong evidence that it is cost-effective to adapt budgets and/or take preventive actions to improve the resilience of roadway infrastructure.

Table 8-3. Summary of Costs Included in the Two Road Response Scenarios

Source: Neumann et al. (2021).

Reactive Response Scenario	Proactive Adaptation Scenario
Costs include: • Repair costs for extreme-temperature damage to paved road surfaces, washouts of unpaved roads from extreme precipitation events, and ruts caused by freeze–thaw damage. • Costs of delays from unplanned repairs, which typically last longer than those for planned repairs because of time needed to mobilize repair crews.	Costs include: • Upfront capital costs for proactive strengthening completed during scheduled maintenance and rehabilitation (e.g., using asphalt binders designed for higher future temperatures). • All repair costs considered in the reactive scenario, potentially reduced through investments in more resilient materials during routine maintenance and rehabilitation. • Costs of delays due to proactive (planned) strengthening and repairs.
Costs do not include: • Routine (non-climate–driven) maintenance costs	Costs do not include: • Routine (non-climate–driven) maintenance costs.

2.1.2 Results

Figure 8-1 shows the annual costs relative to a 1981–2010 baseline for both response scenarios, indicating how the different response strategies compare with each other, under both SSP2-4.5 and SSP5-8.5. The proactive adaptation scenario results in the lowest costs above baseline under both SSP2-4.5 and SSP5-8.5. In the proactive strategy, consideration of future climate change over the anticipated useful life of the infrastructure begins to diverge from current and recent historical climate as soon as the 2030s, meaning that impacts are below the reactive scenario in the 2030s. Under SSP2-4.5, impacts under the proactive scenario decrease from the 2030s through the 2080s because proactive investments in road surface resilience in early eras reduce costs later in the century. For SSP5-8.5, impacts under the proactive scenario also increase from the 2030s to 2050s, as the pace of proactive investment is required to be higher to keep up with temperature and precipitation stressors, but decrease from the 2050s to 2080s as those investments yield benefits later in the century. Under SSP5-8.5, proactive adaptation scenario costs increase by about \$90 million from the 2030s to 2050s and decrease by about \$115 million from the 2050s to 2080s.

Figure 8-1. Annual Economic Impacts on Roadway Infrastructure Due to Climate Change by Adaptation Scenario

Estimates are shown in billions of USD and represent the average annual costs by adaptation scenario for the period indicated on the horizontal axis. Shown are results for SSP2-4.5 (top) and SSP5-8.5 (bottom)

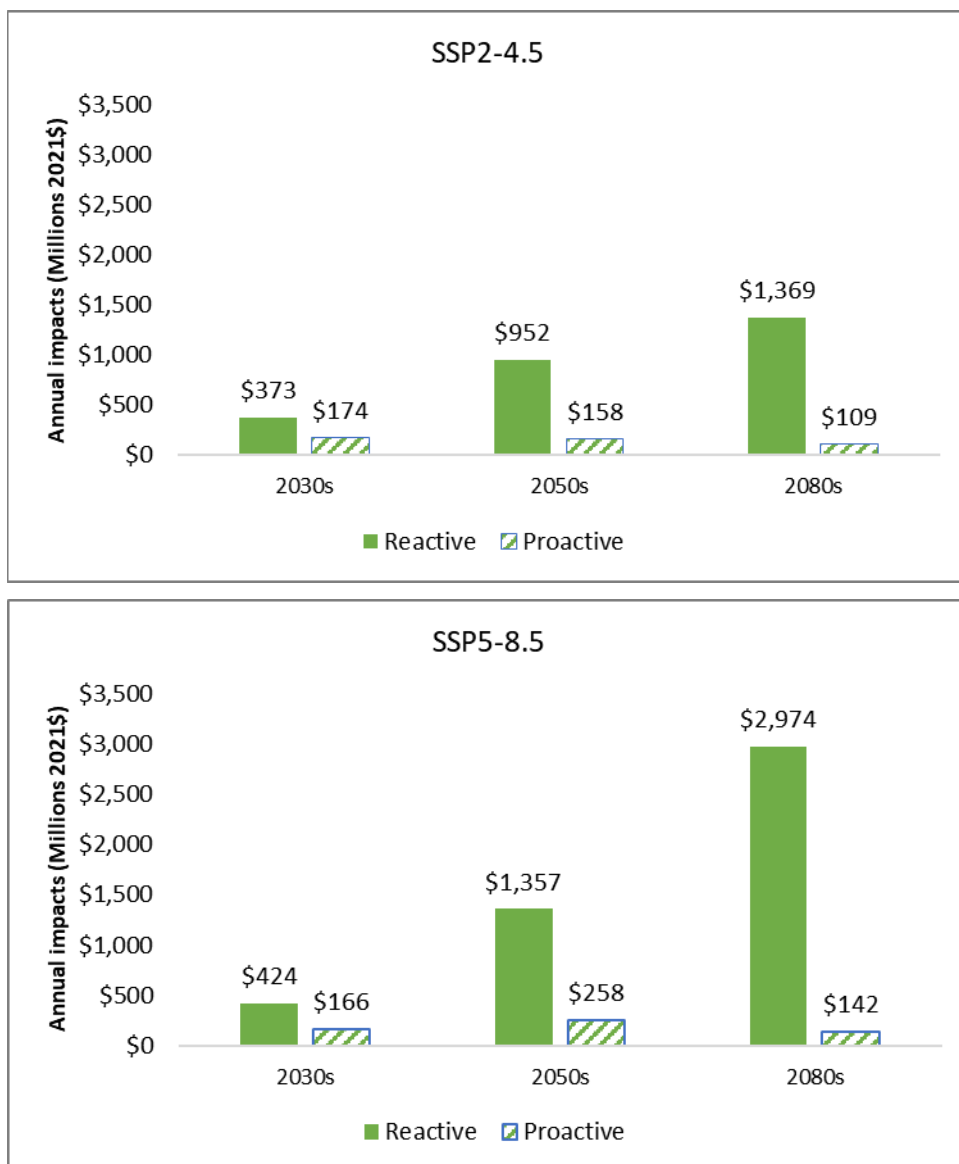


Table 8-4 and Table 8-5 show these impacts by region for all three eras and both SSP2-4.5 and SSP5-8.5 for both scenarios, Figure 8-2 shows the impacts by county for SSP2-4.5 and SSP5-8.5. Under the reactive scenario, the Great Lakes region has the largest impact, followed by the Central/Finger Lakes and North Hudson. The lowest impacts are again in the Adirondacks, the Champlain Valley, and the St. Lawrence Valley.

For both the reactive response and the proactive adaptation scenarios, the spatial distributions of impacts are consistent with the distribution of roads across New York State. The Great Lakes region accounts for the largest portion of the State's road lane miles (18.4%), and the Champlain Valley, St. Lawrence Valley and Adirondacks all account for less than 4%.

Under the proactive scenario, the largest impacts are in Long Island, North Hudson, and the Southern Tier, while the lowest impacts occur in the St. Lawrence Valley, the Champlain Valley, and the Catskills. The spatial and temporal distribution of impacts for the proactive scenario differs from the distribution for the reactive response scenario due to differences in the effectiveness of capital investments that lessen current and future repair costs. For example, in the Great Lakes region, midcentury investments in high-temperature asphalt binders lead to much lower asphalt repair costs in the late-century period, reducing those costs below baseline repair costs. Several other regions, a similar pattern of proactive investment in the midcentury period yielding lower operating costs in the late-century period is also evident, but in those other regions the reduction in operating costs is lessened because it is more difficult to perfectly optimize proactive adaptation investments.²

Under both SSP2-4.5 and SSP5-8.5, impacts are highest in Suffolk County at about \$62 and \$86 million, respectively, and lowest in Hamilton County at only \$3 million and \$5 million, respectively.

² In general, capital investments in more climate resilient road materials reduces the need for future climate-induced repairs, and while it is unusual that those repair costs would be less than the baseline climate repair costs, that result can happen in some areas, as in Table 8-4 for the Great Lakes. Also, some differences across regions and time periods result from the lack of perfect foresight about future temperatures in the model.

Table 8-4. Annual Economic Impacts on Roadway Infrastructure Due to Climate Change by Region for the Reactive Response Scenario, by Region

Change from baseline. Economic impacts represent the estimated additional cost due to climate change required to maintain road infrastructure under a reactive response scenario. Results are reported in millions of 2021 USD per year and averaged across GCMs. Values may not sum due to rounding.

Source: Neumann et al. (2021).

Region	Near Century (2030s)		Midcentury (2050s)		Late Century (2080s)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Adirondacks	\$13.60	\$14.30	\$27.80	\$41.90	\$40.50	\$105.00
Catskills	\$14.90	\$18.60	\$54.40	\$77.40	\$77.40	\$171.00
Central/Finger Lakes	\$43.90	\$50.01	\$125.00	\$171.00	\$173.00	\$351.00
Champlain Valley	\$14.30	\$15.10	\$24.20	\$34.30	\$31.90	\$74.70
Great Lakes	\$117.00	\$134.00	\$183.00	\$256.00	\$261.00	\$577.00
Long Island	\$18.80	\$23.20	\$100.00	\$152.00	\$144.00	\$303.00
Mohawk River Valley	\$19.30	\$23.60	\$79.60	\$113.00	\$109.00	\$229.00
New York City	\$11.60	\$12.80	\$57.70	\$86.50	\$88.40	\$199.00
North Hudson	\$59.80	\$63.40	\$103.00	\$143.00	\$152.00	\$310.00
South Hudson	\$5.90	\$7.29	\$86.60	\$121.00	\$126.00	\$277.00
Southern Tier	\$48.90	\$55.20	\$92.90	\$131.00	\$137.00	\$292.00
St. Lawrence Valley	\$5.30	\$7.04	\$17.60	\$30.50	\$29.00	\$84.40
Statewide	\$373.00	\$424.00	\$952.00	\$1,357.00	\$1,369.00	\$2,974.00

Table 8-5. Annual Economic Impacts on Roadway Infrastructure Due to Climate Change by Region for the Proactive Adaptation Scenario, by Region

Change from baseline. Economic impacts represent the estimated additional costs due to climate change to maintain road infrastructure, assuming a proactive adaptation scenario. Results are reported in millions of 2021 USD per year and averaged across GCMs. Values may not sum due to rounding.

Source: Neumann et al. (2021).

Region	Near Century (2030s)		Midcentury (2050s)		Late Century (2080s)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Adirondacks	\$13.20	\$12.50	\$11.03	\$15.05	\$8.19	\$11.20
Catskills	\$7.33	\$7.11	\$3.94	\$6.69	\$3.24	\$7.04
Central/Finger Lakes	\$8.83	\$7.05	\$17.30	\$21.50	\$7.51	\$7.06
Champlain Valley	\$13.20	\$11.70	\$7.65	\$9.22	\$3.41	\$4.04
Great Lakes	\$45.10	\$47.80	\$5.39	\$12.01	-\$20.70	-\$17.40
Long Island	\$11.20	\$14.10	\$27.70	\$56.30	\$23.80	\$28.20
Mohawk River Valley	\$5.36	\$4.16	\$15.80	\$22.10	\$16.90	\$25.70
New York City	\$10.80	\$10.90	\$13.83	\$29.60	\$19.90	\$15.20
North Hudson	\$25.50	\$21.90	\$10.90	\$18.03	\$16.70	\$25.20
South Hudson	-\$1.34	-\$5.29	\$23.20	\$40.20	\$20.40	\$26.04
Southern Tier	\$29.20	\$29.30	\$17.20	\$21.20	\$6.81	\$7.35
St. Lawrence Valley	\$5.63	\$5.23	\$3.71	\$5.98	\$2.84	\$1.96
Statewide	\$174.00	\$166.00	\$158.00	\$258.00	\$109.00	\$142.00

Figure 8-2. Annual Impacts of Climate Change Road Infrastructure for SSP2-4.5 (left) and SSP5-8.5 (right) by County, Reactive Scenario, 2050

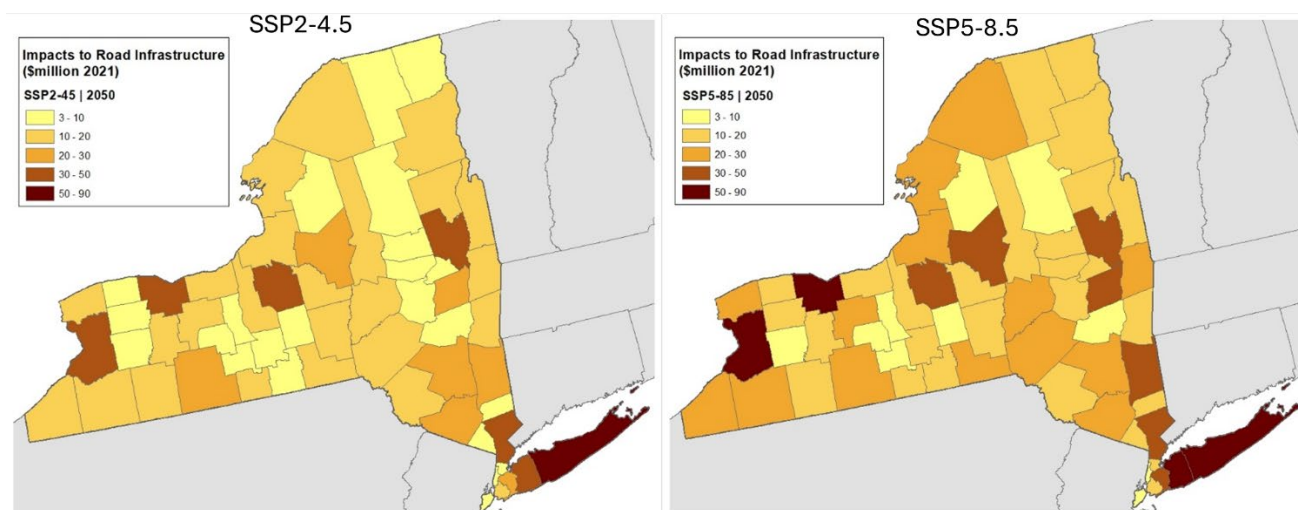


Figure 8-3 shows the impacts above baseline by jurisdiction (federal, State, local, private, and Tribal) for the reactive scenario under both SSP2-4.5 and SSP5-8.5. The largest roadway climate change impacts for New York State are in the State and local jurisdictions. A small proportion of the costs are in the remaining jurisdictions of federal, private, and tribal Nations. The pattern shown in the figure where State and local jurisdiction costs make up the majority of total costs was also reflected in the proactive adaptation scenario, although the magnitude of total costs above baseline differed as expected, where magnitudes decrease.

Figure 8-3. Impacts above Baseline of Climate Change on Road Infrastructure by Jurisdiction for SSP2-4.5 and SSP5-8.5, Reactive Scenario, 2020–2099

Source: Neumann et al. (2021).

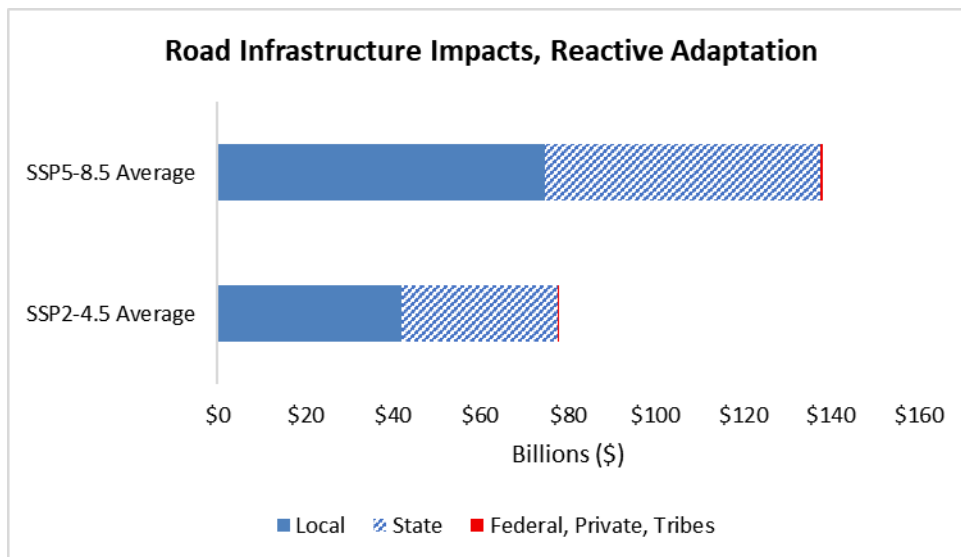
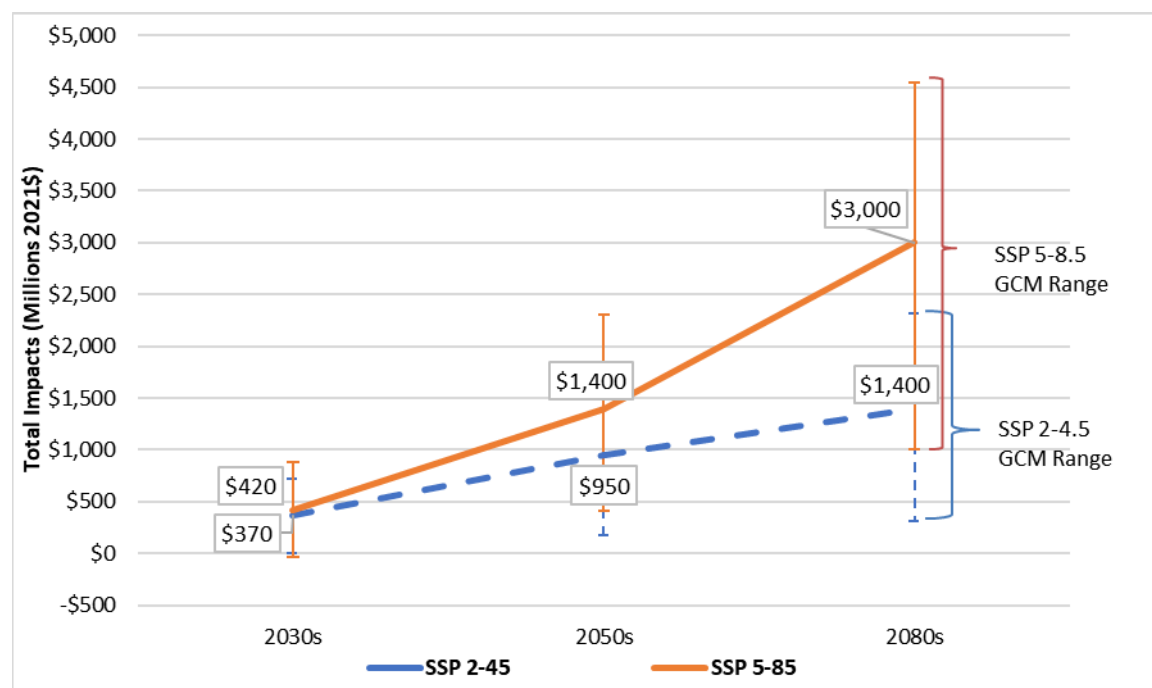


Figure 8-4 shows the impacts by era for the reactive response scenario for both SSPs, for the average across GCMs as indicated by the horizontal line, as well as the range across GCMs, indicated by the vertical lines and whiskers. The range across the GCMs is substantial for all response scenarios, SSPs, and eras and ranges between about \$800 million for the 2030s to roughly \$2 billion in the 2050s and almost \$5 billion in the 2080s for SSP2-4.5 and SSP5-8.5. For the proactive scenario, the ranges vary in magnitude but are similar relative to the mean across the GCMs, except that the proactive scenario includes a cost increase from 2030s to 2050s for SSP5-8.5. This increase is triggered by Capital investment in resilient materials in the midcentury era, which results in reduced repair costs in the late-century period.

Figure 8-4. Impacts above the Baseline (1981–2010 Average) Due to Climate Change by Era, Including the Range across Global Climate Models, Reactive Scenario

Source: Neumann et al. (2021).



2.1.3 Limitations and Assumptions

This analysis includes several limitations related to data, modeling assumptions, and scope, which may affect the interpretation and generalizability of the results.

- This analysis quantifies the first-order effects of transportation delays as a loss in available time. secondary impacts, such as lost productivity in multiple economic sectors, are not estimated.
- The analysis does not model vehicle damage associated with incompletely maintained roads. The model assumes prompt road repair under both the reactive and proactive scenarios, resulting in no vehicle damage.
- The analysis includes only a limited set of proactive adaptation measures. Other strategies, such as changing culvert replacement schedules or redesigning culverts to reduce roadway washouts, could further reduce damage.
- For discussion of the limitations and assumptions in the underlying sectoral model, see Neumann et al. (2014, 2021) and EPA (2017).

2.2 Rail

The scope of economic impacts considered includes the costs of extreme temperature-induced train speed reductions, which cause passenger and freight delays, costs to repair rail infrastructure failures, and incremental damage associated with heat stress.

Temperature changes due to climate change can affect the structural integrity of railroad tracks throughout New York State. The impacts result from Thermal expansion of rails during high heat events, which in cases of moderate heat stress leads to a reduction in train speeds to avoid further heating and potential damage of the rails. In more extreme cases, heat stress can cause deformation of rails, which requires repair, without which the risk of derailment may increase to unacceptably high levels.

Steel tracks are designed to operate in a narrow range that is based on the temperature in which it is originally laid, known as the design neutral temperature. When this temperature is exceeded, the ability of the steel rails to support rail traffic begins to degrade.³ Under extreme heat conditions, the continuously welded rail tracks that make up the modern rail system will buckle due to expanding metal. For example, a typical welded length of 1,800 feet of rail can expand up to 1 inch per 10 degrees Fahrenheit (°F) increase in temperature (Wolf 2005). In extreme heat conditions where temperature increases can be several times that magnitude, expansion and offset can quickly exceed several inches, which can lead to derailment if undetected. These expansion conditions are known as “sun kinks” and can lead to failure if rail traffic is not reduced until temperatures decline.

This analysis estimates the economic impact of thermal rail expansion based on Neumann et al. (2021) and Chinowsky et al. (2019), which assess the effects of climate drivers on the railroad sector. The costs are based on changes to repair activities at the time that a climate stressor causes damages to the infrastructure and delays associated with speed reduction.

2.2.1 Methodology

This rail analysis uses a consistent analytic framework to evaluate impacts of climate change under two alternative infrastructure management scenarios: reactive response and proactive adaptation. Both scenarios consider reduced train speeds leading to delays; however, the proactive response incorporates rail temperature sensors to optimize the use of speed controls in order to minimize those delays. The analysis quantifies the impact of increased temperatures on the rail system under each scenario, incorporating two components:

³ This analysis only examines exceedances of design-neutral temperatures, as the authors are unaware of any documented instances of rail slowdown rules, rail deformity, or derailments associated with cold temperatures.

1. Estimating potential increases in buckling failures
2. Estimating potential increases in temperature-based delays

The former is required to determine the increased likelihood that track buckles will result in subsequent operation delays. The increase in buckling potential triggers an accepted operating procedure that requires trains to reduce speed during conditions that may result in increased buckling. Once the potential for increased buckling is identified, the second element estimates potential increases in rail delays in accordance with the operating procedures that reduce speeds due to safety considerations. More details of the methods and response scenarios are described in the supplemental material of Neumann et al. (2021) and in Appendix B of this report.

Table 8-6. Summary of Costs Included in the Two Rail Response Scenarios

Source: Neumann et al. (2021).

Reactive Response Scenario	Proactive Adaptation Scenario
Costs include: • Replacing track to repair lateral alignment defects in the buckling zone and realigning rail in adjoining zones • Delays that occur due to track buckling and repair, as well as delays associated with blanket speed reductions • Derailments that may result from track buckling • Developing and implementing speed orders	Costs include: • Upfront capital costs for purchasing, installing, and maintaining track temperature sensors and related software infrastructure. • Delays associated with risk-based speed reductions • Downtime during sensor installation (believed to be minimal)
Costs do not include: • Routine (non-climate-driven) track maintenance costs	Costs do not include: • Routine (non-climate-driven) track maintenance costs

2.2.2 Results

Figure 8-5 shows the annual costs relative to a 1981–2010 baseline for both response scenarios, indicating how the two response strategies compare with each other, under both SSP2-4.5 and SSP5-8.5. For the reactive scenario Under SSP2-4.5, costs increase by about \$250 million from the 2030s to 2050s, but then decline by about \$250 million to about \$500 million from the 2050s to 2080s. This is due to two factors in the modeling: first, temperature spikes begin to moderate in the late century in this lower emissions scenario; second, the reactive replacement of some buckled track in the midcentury period at the higher temperatures at midcentury effectively resets those sections of track to a condition that resists some of the buckling that might otherwise result in the late century. Under SSP5-8.5, with more rapid warming throughout the simulation period, costs increase by about \$600 million from the 2030s to 2050s and by about another \$2 billion from the 2050s to 2080s.

In the proactive adaptation strategy, consideration of future climate change over the anticipated useful life of the infrastructure begins to diverge from current and recent historical climate as soon as the 2030s. Cost magnitudes are substantially lower for the proactive scenario than the reactive scenario across all eras. For both SSP2-4.5 and SSP5-8.5, impacts under proactive scenarios increase slightly between the 2030s and the 2050s and again between the 2050s and the 2080s. Under SSP2-4.5, costs increase by about \$15 million from the 2030s to 2050s and by about \$50 million from the 2050s to the 2080s. Under SSP5-8.5, costs increase by about \$20 million from the 2030s to the 2050s, but decrease by about \$95 million from the 2050s to the 2080s. The large difference between the reactive and proactive scenarios represents the substantial value of information provided by the temperature sensor network, allowing operators to much more precisely target slowdowns to only those periods and sections of track where the risk of buckling is measurably greater.

Figure 8-5. Annual Economic Impacts above the Baseline (1981–2010 Average) on Rail Infrastructure Due to Climate Change by Response Scenario, SSP2-4.5

Values reported in millions of 2021 USD.



Table 8-7 and Table 8-8 show these impacts by region for all three eras and both SSP2-4.5 and SSP5-8.5 for the reactive and proactive scenarios; Figure 8-6 shows the impacts by county for SSP2-4.5 and SSP5-8.5 for the reactive response scenario in the 2050s. Under both SSP2-4.5 and SSP5-8.5, impacts are highest in Nassau County at about \$250 million and \$380 million per year, respectively, owing to its extensive and high traffic passenger and rail network, and lowest in Franklin County at less than \$1000 and \$1500 per year, respectively, a county with no passenger rail service and only a small amount of lightly used freight rail mileage in its northwest and southwest corners. The Long Island region has the

largest total impacts, followed by New York City and South Hudson region. The regions with the lowest impacts under both the reactive and the proactive scenarios are the Southern Tier, St. Lawrence Valley, and the Adirondacks. For the most part, these patterns can be explained by the amount of infrastructure exposed to climate. Manhattan borough in New York City, for example, has almost exclusively underground subway lines, but other boroughs have more extensive above-ground components.

Table 8-7. Annual Economic Impacts on Rail Infrastructure Due to Climate Change by Region for the Reactive Response Scenario, by Region

Reactive response. Economic impacts represent the estimated additional costs due to climate change to maintain rail infrastructure, assuming a reactive scenario. Results are reported in millions of 2021 USD per year and averaged across GCMs. Values may not sum due to rounding.

Source: Analysis based on Neumann et al. (2021).

Region	Near Century (2030s)		Midcentury (2050s)		Late Century (2080s)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Adirondacks	\$0.03	\$0.04	\$0.06	\$0.13	\$0.06	\$0.64
Catskills	\$0.91	\$1.36	\$2.29	\$5.47	\$2.00	\$30.30
Central/Finger Lakes	\$2.64	\$3.38	\$4.18	\$9.31	\$3.27	\$62.80
Champlain Valley	\$0.19	\$0.25	\$0.32	\$0.80	\$0.29	\$4.25
Great Lakes	\$3.04	\$3.76	\$4.35	\$8.08	\$3.58	\$46.50
Long Island	\$244.00	\$280.00	\$370.00	\$551.00	\$223.00	\$1,429.00
Mohawk River Valley	\$4.04	\$5.61	\$6.98	\$19.10	\$5.23	\$124.00
New York City	\$144.00	\$170.00	\$206.00	\$324.00	\$141.00	\$864.00
North Hudson	\$2.68	\$3.77	\$3.57	\$8.76	\$3.10	\$55.60
South Hudson	\$98.10	\$118.00	\$155.00	\$251.00	\$98.10	\$714.00
Southern Tier	\$0.20	\$0.25	\$0.29	\$0.54	\$0.30	\$2.77
St. Lawrence Valley	<\$0.01	<\$0.01	\$0.01	\$0.01	\$0.01	\$0.04
Statewide	\$500.00	\$587.00	\$753.00	\$1,179.00	\$480.00	\$3,335.00

Table 8-8. Annual Economic Impacts on Rail Infrastructure Due to Climate Change by Region for the Proactive Adaptation Scenario, by Region

Proactive adaptation. Economic impacts represent the estimated additional costs due to climate change to maintain rail infrastructure, assuming a proactive adaptation scenario. Results are reported in millions of 2021 USD per year and averaged across GCMs. Values may not sum due to rounding.

Source: Analysis based on Neumann et al. (2021).

Region	Near Century (2030s)		Midcentury (2050s)		Late Century (2080s)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Adirondacks	\$0.02	\$0.03	\$0.08	\$0.12	\$0.54	\$1.03
Catskills	\$0.08	\$0.11	\$0.57	\$0.83	\$1.99	\$3.62
Central/Finger Lakes	\$0.20	\$0.25	\$0.87	\$1.31	\$3.71	\$6.84
Champlain Valley	\$0.06	\$0.09	\$0.38	\$0.61	\$1.58	\$2.93
Great Lakes	\$0.30	\$0.34	\$0.95	\$1.40	\$4.84	\$9.56
Long Island	\$2.39	\$2.57	\$7.25	\$9.35	\$19.70	\$34.5
Mohawk River Valley	\$0.17	\$0.22	\$1.23	\$1.96	\$6.00	\$11.3
New York City	\$1.11	\$1.19	\$2.68	\$3.42	\$6.69	\$11.5
North Hudson	\$0.26	\$0.35	\$1.02	\$1.60	\$4.88	\$9.12
South Hudson	\$1.41	\$1.57	\$5.30	\$7.10	\$16.90	\$30.20
Southern Tier	\$0.09	\$0.10	\$0.28	\$0.39	\$1.46	\$2.67
St. Lawrence Valley	<\$0.01	<\$0.01	\$0.01	\$0.02	\$0.08	\$0.16
Statewide	\$6.11	\$6.82	\$20.60	\$28.10	\$68.50	\$123

Figure 8-6. Annual Impacts of Climate Change Rail Infrastructure for SSP2-4.5 (top) and SSP5-8.5 (bottom) by County, Reactive Response, 2050s

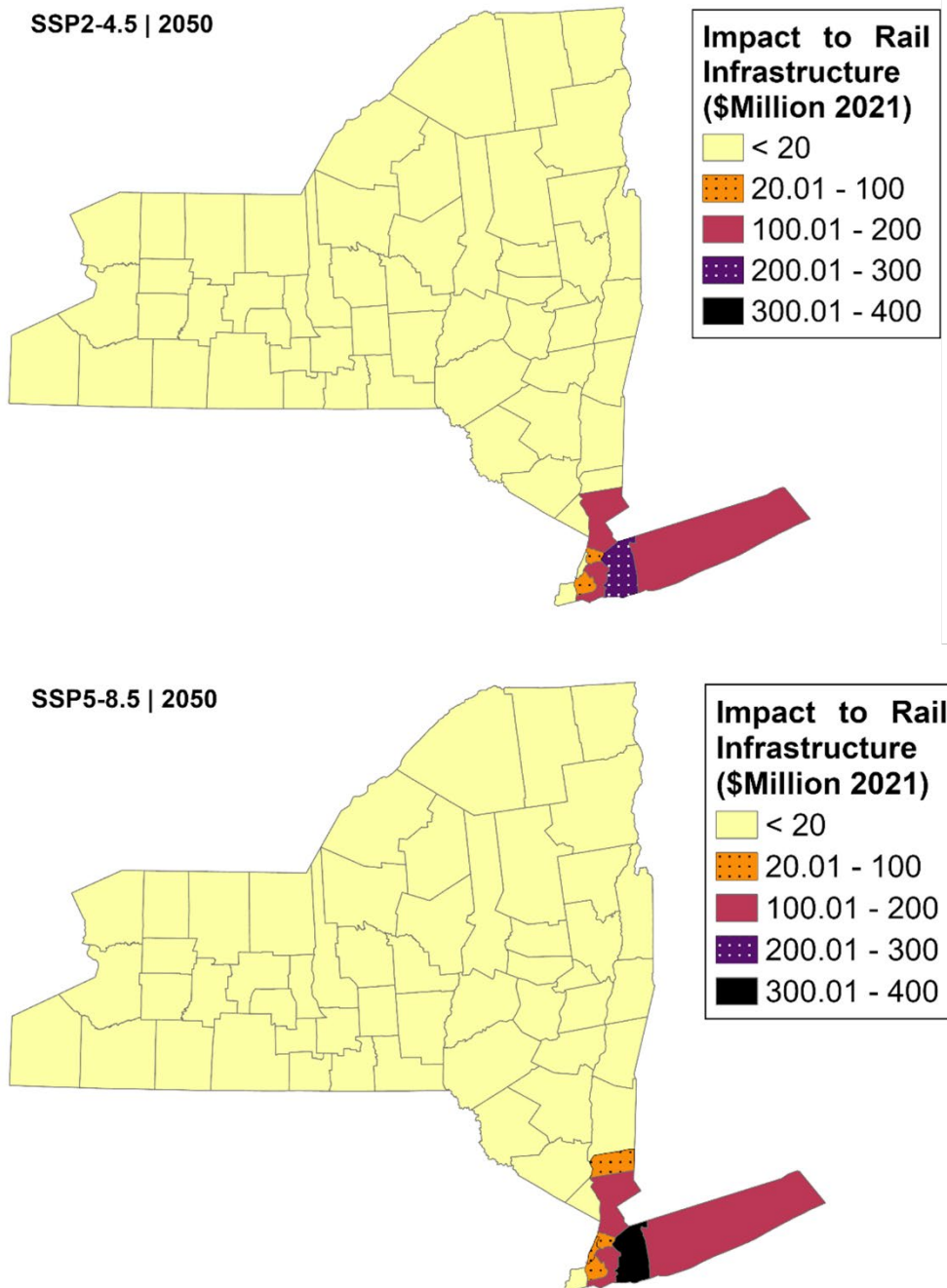


Figure 8-7 shows the cumulative impacts above the baseline through this century by type (repair and delay costs) for the reactive scenario. Delay costs of climate impacts on rail infrastructure create the largest impacts for New York State. A relatively small proportion of the costs come from direct repair costs, emphasizing the importance of modeling indirect delay costs to better understand the climate impacts on this industry. Neumann et al. (2021) describe repair costs as those for replacing track to repair lateral alignment defects in the buckling zone and costs of re-aligning rail in adjoining zones. They define costs of delays as those occurring due to track buckling and repair, as well as delays associated with blanket speed reductions. The pattern shown in the figure (where delay costs make up the majority of total costs) was also reflected in the proactive adaptation scenario, although the magnitude of total costs above baseline was much lower in the proactive scenario, as expected.

Figure 8-7. Cumulative Impacts above Baseline of Climate Change on Rail Infrastructure for SSP2-4.5 and SSP5-8.5, Reactive Response, 2020–2099

Source: Analysis based on Neumann et al. (2021).

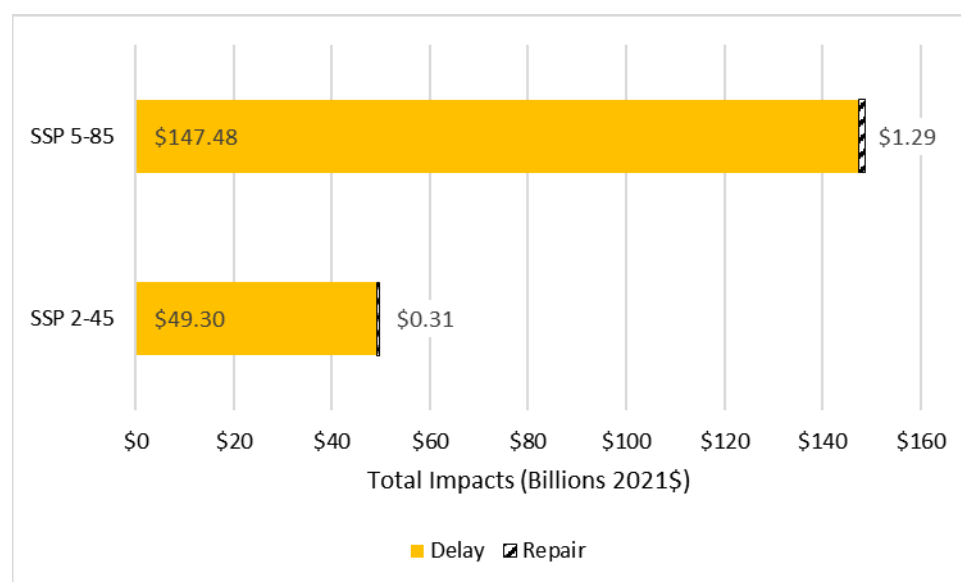
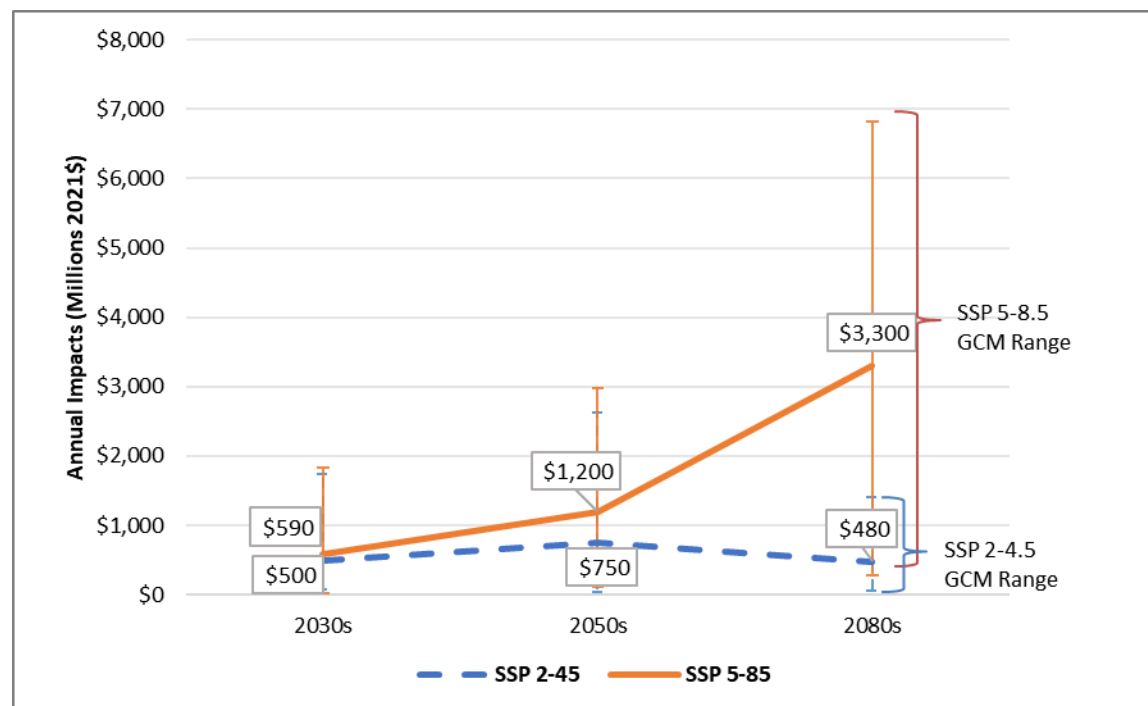


Figure 8-8 shows the annual costs relative to the 1981–2010 baseline by era for the reactive scenario under both SSPs, for the average across GCMs, and the range across GCMs, indicated by the vertical lines and whiskers. The range across the GCMs is substantial for all response scenarios, SSPs, and eras and ranges between about \$2 billion for the 2030s to roughly \$3 billion in the 2050s. In the 2080s era, the range is about \$2 billion under SSP2-4.5 and \$7 billion under SSP5-8.5. For the proactive adaptation scenario, the range varies in magnitude but is similar relative to the mean across the GCMs.

Figure 8-8. Annual Impacts above the Baseline (1981–2010 Average) on Rail Infrastructure Due to Climate Change by Era, Including the Range across Global Climate Models, Reactive Response

Source: Analysis based on Neumann et al. (2021).



2.2.3 Limitations and Assumptions

- This analysis quantifies the first-order effects of transportation delays as losses in available time. It does not account for secondary impacts such as lost productivity across multiple economic sectors.
- The model assumes the number of rail miles remains fixed over time. Rail traffic over the existing network grows with a weighted average of population growth (for the passenger rail component) and economic growth (for the much larger freight rail component).
- The analysis equipment, labor, and repair supply costs are assumed to remain constant.
- The analysis did not include impacts due to flooding of underground track, which would add costs under both scenarios.
- For further discussion of the limitations and assumptions in the underlying sectoral model, see Neumann et al. (2021) and Chinowsky et al. (2019).

2.3 Coastal Roads

The scope of economic impacts considered includes the costs of road user delays associated with flooding of roads due to periodic high-tide flooding; costs to raise or protect roads from flooding when cost-effective.

High-tide flooding (HTF) events, sometimes referred to as nuisance flooding or sunny day flooding, are minor flooding events caused by tidal variations. Typically, HTF events are distinguished from more extreme coastal flood events, such as hurricane-driven storm surge, and historically have not caused major damage to coastal property. However, rising seas elevate the base level upon which tides act, therefore leading to inland expansion of the tidal zone over time. HTF events impact low-lying infrastructure, such as roads and traffic, as well as underground stormwater systems, sewer systems, and wires. Despite having lower impacts per event compared to tropical storms, HTF events happen more often, and as a result may cause equal or more damage each year than extreme events. One of the largest impacts of HTF events is traffic delays caused by floods across road networks, causing additional congestion and longer travel times.

Traffic delays from HTF events are characteristically different from delays caused by increased temperatures or precipitation. Roads vulnerable to HTF are those with low-points or low-lying stretches near the coast and are identified using location-specific attributes. While there are far fewer roads vulnerable to HTF compared to temperature or precipitation hazards, delays caused by tidal flooding inundation can be extensive for each road and increase with higher sea levels. While adapting roads to avoid delays is expensive, increasing the elevation of the low points can effectively eliminate HTF-caused delays.

Jacobs et al. (2018a) found that delays would increase substantially along the East Coast due to sea level rise, reaching 1.2 billion vehicle hours by 2060 and 3.4 billion by 2100, whereas delays currently are roughly 100 million vehicle hours. Fant et al. (2021) extends Jacobs et al. to provide an estimate of monetary impacts using a value-per-hour loss to drivers that includes time-values, vehicle operation and maintenance costs, and costs associated with delays in the transportation of goods.

Adapting to HTF flooding effects is likely to be cost effective, particularly in areas where dense road networks allow for rerouting of the potentially affected traffic. However, not all aspects of HTF flooding can be alleviated by rerouting. In this report, The analysis considers two response scenarios—reactive response and proactive adaptation—to capture uncertainty in the future response to this coastal hazard.

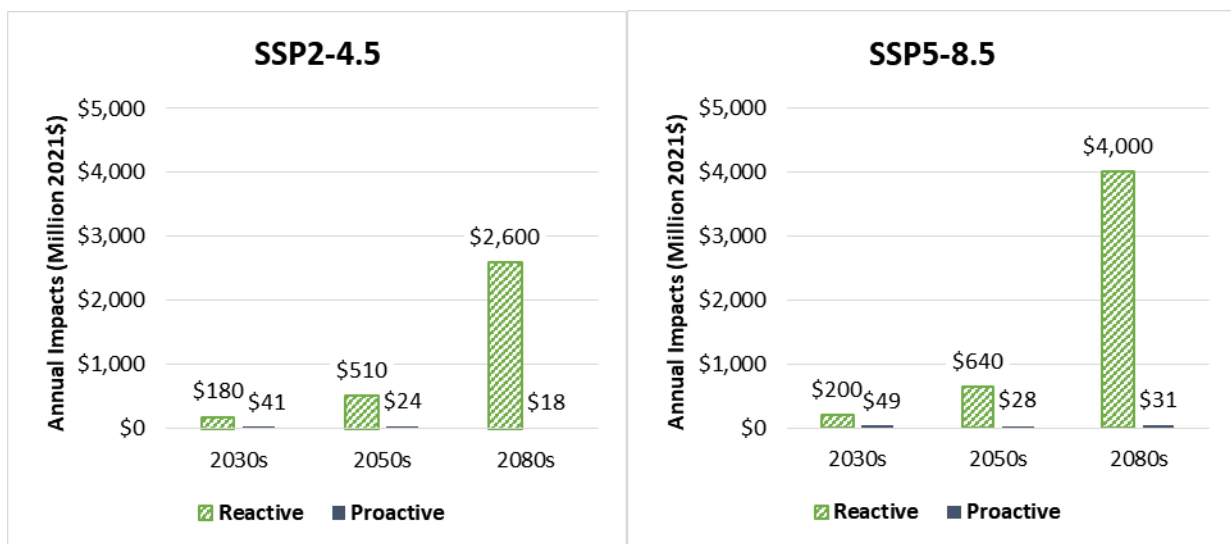
2.3.1 Methodology

Fant et al. (2021) developed a five-step approach for estimating impacts. Appendix B details the method and the data sources used.

1. Determine the hourly distribution of tide-gauge water levels for future sea levels.
2. Segment the road network by intersections or ramps and assign traffic data to each segment.
3. Use these datasets together with floodplain mapping to identify vulnerable roads and flood duration.
4. Calculate roadway risk, measured in vehicle hours of delay, as the product of flood duration and traffic, then monetize risk using hourly delay rates for passenger vehicles and freight trucks.
5. Simulate two response types:
 - Reactive response, including driver-initiated rerouting and ancillary protection from property-protection actions
 - Proactive adaptation, which adds actions such as raising the road profile above flood height or constructing hard structures, such as seawalls or bulkheads, to further reduce delays

Figure 8-9. Annual Economic Impacts on Coastal Roads Due to Sea-Level Rise by Response Scenario

Annual economic impacts on coastal roads due to sea-level rise (in million 2021 USD) by response scenario for SSP2-4.5 (left) and SSP5-8.5 (right), relative to a 2005 baseline.



2.3.2 Results

Figure 8-10 shows the costs for the two response scenarios, reactive response and proactive adaptation. Under the reactive response scenario, impacts rise rapidly from \$180 million to \$200 million per year in the 2030s to about \$2,600 million to \$4,000 million in the 2080s. The differences between SSP2-4.5 and SSP5-8.5 increase over time, from about \$20 million per year in the 2030s to \$1.4 billion per year in the 2080s. The proactive adaptation scenario is significantly lower than reactive in all eras. Under SSP2-4.5 with proactive adaptation, impacts decline over time as roads are raised or protected with seawalls. Under SSP5-8.5, impacts decline from the 2030s to the 2050s but then increase slightly in the 2080s, indicating the additional pressure of sea-level rise on traffic delays with these levels of greenhouse gases (GHGs).

Table 8-9 and Table 8-10 show regional impacts for all three eras and both SSP2-4.5 and SSP5-8.5 for the reactive scenario and proactive scenario. Figure 8-10 shows the impacts by county for SSP2-4.5 for the reactive scenario in the 2050s.

New York City has the highest impacts, increasing from \$161 million to \$174 million per year in the 2030s to 15–21 times higher in the 2080s. This region bears about 85% to 90% of the total costs for the reactive scenario because of its dense, low-lying, highly trafficked road network. The Long Island region is expected to experience most of the remaining impacts for the reactive scenario, with costs rising from \$18 million to \$27 million per year in the 2030s to 13–14 times higher in the 2080s.

The proactive scenario tells a different story, with all regions showing a decrease in impacts from the 2030s to the 2080s. In the Long Island region, impacts decline from the 2050s to the 2080s for SSP2-4.5 but increase slightly under SSP5-8.5 (though still lower than the 2030s). That is less the case for the New York City region where costs remain more consistent from the 2050s to the 2080s for both SSPs. The New York City region benefits the most from proactive adaptation, followed by the Long Island region. For the other three regions, impacts are slightly higher in the proactive region in the 2030s but lower in the 2080s, highlighting the potential for adaptation to result in higher up-front costs with benefits later in the century as conditions worsen.

Table 8-9. Annual Economic Impacts on Coastal Roads Due to Sea-Level Rise by Region for the Reactive Response Scenario, by Region

Reactive response. Change from baseline (2005). Economic impacts represent the estimated additional costs due to climate change from sea-level rise relative to 2005, assuming a reactive response scenario. Results are reported in millions of 2021 USD annually, and these are the average of the 25th- and 75th-percentile sea-level rise scenarios for each SSP. Values may not sum due to rounding.

Source: Analysis based on Fant et al. (2021).

Region	Near Century (2030s)		Midcentury (2050s)		Late Century (2080s)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Catskills	\$0.1	\$0.1	\$0.2	\$0.2	\$0.8	\$1.6
Long Island	\$18.4	\$27.0	\$49.7	\$61.7	\$236.0	\$380.0
New York City	\$161.0	\$173.7	\$456.1	\$572.7	\$2,391.2	\$3,663.7
North Hudson	\$0.1	\$0.1	\$0.2	\$0.2	\$0.7	\$1.4
South Hudson	\$0.0	\$0.1	\$0.1	\$0.1	\$0.5	\$0.8
Statewide	\$179.6	\$201.0	\$506.2	\$635.0	\$2,629.2	\$4,047.4

Table 8-10. Annual Economic Impacts on Coastal Roads Due to Sea-Level Rise by Region for the Proactive Adaptation Scenario, by Region

Proactive adaptation. Change from baseline (2005). Economic impacts represent the estimated additional cost due to climate change from sea-level rise relative to 2005, assuming a proactive adaptation scenario. Results are reported in millions of 2021 USD annually, and these are the average of the 25th- and 75th-percentile sea-level rise scenarios for each SSP. Values may not sum due to rounding.

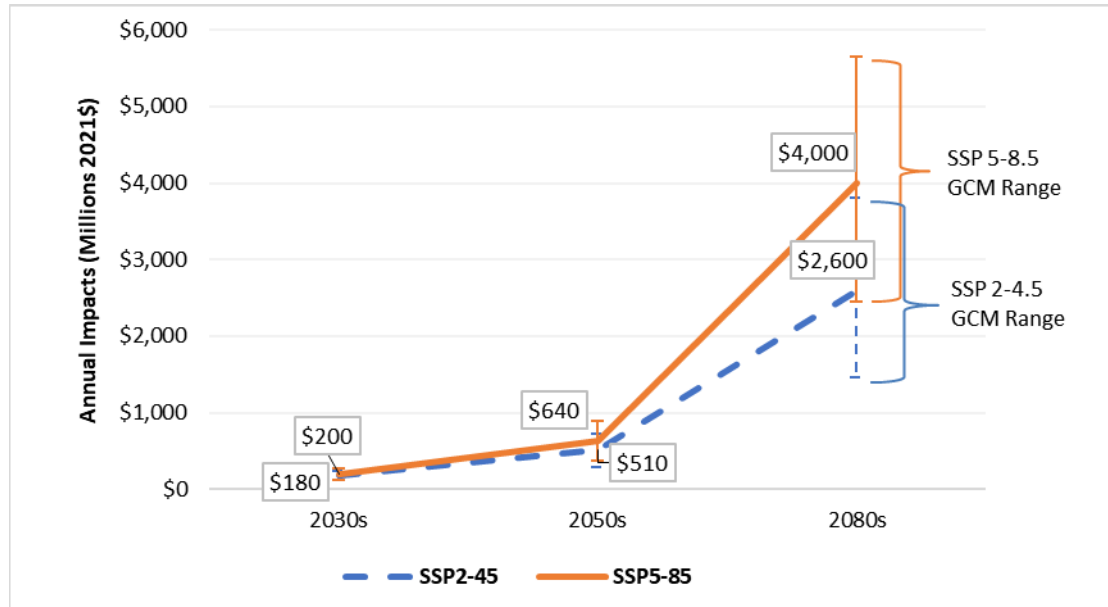
Source: Analysis based on Fant et al. (2021).

Region	Near Century (2030s)		Midcentury (2050s)		Late Century (2080s)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Catskills	\$0.3	\$0.4	\$0.2	\$0.3	\$0.4	\$0.4
Long Island	\$20.4	\$22.4	\$15.6	\$15.0	\$9.1	\$17.8
New York City	\$19.3	\$25.4	\$8.0	\$12.2	\$8.0	\$11.6
North Hudson	\$0.4	\$0.4	\$0.2	\$0.2	\$0.3	\$0.5
South Hudson	\$0.2	\$0.2	\$0.3	\$0.4	\$0.4	\$0.4
Statewide	\$40.6	\$48.7	\$24.4	\$28.1	\$18.1	\$30.8

Figure 8-10 shows the impacts by era for the reactive scenario for both SSPs, for the average across the 25th- and 75th-percentile sea-level-rise scenarios, and the range between them, indicated by the vertical lines and whiskers. In the 2030s and 2050s, differences between SSPs are less pronounced but they diverge after the 2050s, with greater variation in the latter half of the century. The range across the 25th and 75th percentiles follows a similar pattern, increasing over time so that the upper bound of SSP2-4.5 almost reaches the SSP5-8.5 mean, and the lower bound of SSP5-8.5 drops below the SSP2-4.5 mean.

Figure 8-10. Annual Impacts on Coastal Roads above the 2005 Baseline Due to Sea-Level Rise by Era, Including the Range across the 25th- and 75th-Percentile Sea-Level Rise Scenarios, Reactive Response

Source: Analysis based on Fant et al. (2021).



2.3.3 Limitations

- This analysis quantifies the first-order effects of transportation delays as losses in available time. It does not account for secondary impacts such as lost productivity across multiple economic sectors.
- The analysis uses traffic data from Fant et al. (2021), which is based on 2016 DOT traffic data. These data do not account for potential traffic impacts from the New York City Central Business District Tolling Program, which began on January 5, 2025.
- The analysis applies national average construction delay times from RSMeans (Gordian 2017), which may vary by region. It also bases adaptation and maintenance costs on national average material and labor costs from RSMeans, which may vary locally.
- This analysis relies on limited site-specific information and therefore excludes direct damage to the road surface from flooding, which Fant et al. (2021) assessed only in case studies.
- The analysis includes only road segments within the National Oceanic and Atmospheric Administration (NOAA)-estimated flood extent for the current minor flood level. As sea levels rise, more roads will become vulnerable, increasing potential delays and damage. Fant et al. (2021) estimate that total vulnerable traffic could increase by about 50% by 2050 and more than double by 2100 as a result of incorporating this expanded floodplain.
- In practice, there remain many barriers to implementing cost-effective adaptation in all settings. Technological, behavioral, and financial barriers stand in the way of achieving an economically optimal adaptation outcome. Some of these barriers include:

- Alternative routes: This analysis does not assess road redundancy at a link level. As a result, it is possible the results overestimate the impact of alternative routing to avoid HTF delays. The analysis also does not include additional costs associated with managing road closures and detours. Additionally, the analysis also does not calculate time value effects associated with potentially longer travel times from rerouting, which in some coastal areas can be substantial and could lead to underestimation of road delays.
- Ancillary protection: Homeowners and communities would need to protect properties from sea-level rise and storm surge risk at the right time and location, but there is a risk that coastal protection has less than 100% efficacy in protecting adjoining roads. Some studies (e.g., Lorie et al. 2020) suggest that decisions to invest in coastal property protection are often suboptimal.
- Direct adaptation: The analysis models raising road profiles and constructing seawalls as incremental costs applied during the “next” major rehabilitation cycle (i.e., as an extension of regularly planned and implemented road maintenance). Adding a road-raising option to these projects may complicate permitting and execution, potentially leading to cycles longer than 20 years, thus extending delay time. It may require raising or protecting non-vehicular infrastructure (e.g., above- and below-ground utilities, traffic signals, and sidewalks). These factors could substantially increase the cost of direct adaptation.
- Precipitation and river flooding may prolong traffic delays caused by HTF events. The combined effects of tidal and precipitation-induced flooding are not considered here and are likely to have different characteristics and impacts.
- Absent exact road surface elevations, the realized flood depth is uncertain, and Vehicles may be able to traverse shallow water with only minor speed reductions. This is not considered in this analysis.
- This approach is limited to tide gauge measurements and does not consider situations where flooding is intensified or induced by precipitation.

3 Partially Quantified and Qualitative Damages

Partially quantified impacts are those for which some aspects could be modeled quantitatively, but not robustly enough to be included in the total economic impacts for this sector. Transportation sector impacts that are partially quantified include those on ports and small harbors, air transport, and bridges. economic impacts on ports and small harbors, in the form of adaptation costs to retrofit existing ports, are available but only for a single adaptation scenario that is not connected directly to any sea-level rise scenario. Total damages attributed to recent hurricane strikes are also available but are not parsed to indicate the role of climate in those impacts. Estimates for impacts on air transport are partially quantified for a limited number of airports and airplane class types, indicating the potential for delays or cancellations, but are not connected to economic estimates. Estimates of both physical and economic

impacts on bridges exist for older climate scenarios, but the source is an unpublished working paper that has not been peer-reviewed.

Climate change impacts on subways are addressed qualitatively because there are no available estimates of the economic impacts of climate change on subway operations, capital needs, or additional needs for repairs. The subways section does review available historical damage estimates for a recent hurricane as well as capital budgets set aside for resilience investments, but which are not tied to a specific climate scenario or timing.

3.1 Ports and Small Harbors

Table 8-11. Summary of Climate Change Impacts on Ports and Small Harbors

Element	Description
Description of Impacts	Ports are particularly susceptible to climate-driven flooding and storm damage because they are located directly on coastlines.
Primary Climate Stressors	• Sea-level rise (increased damages) ◦ Rising sea level—increased flood threat, permanent inundation • Extreme weather (increased damages) ◦ More frequent and severe coastal storms—infrastructure damage, flood threat
Economic Values	• Lost revenue • Cost of repair • Cost of adaptation
Primary Affected Regions	East Coast (Port of New York and New Jersey)
Potential Annual Magnitude of Impact in New York State	Greater than \$1 billion by end of century

Port infrastructure is vulnerable to climate change because of its exposure to rising sea level and extreme storms, and Ports are likely to be affected sooner than other key infrastructure because of their shorefront location (Becker et al. 2017). Evidence indicates that New York State’s coasts are already experiencing increased risk of extreme storms and flooding due to climate change (Reed et al. 2015). Rising seas coupled with severe storms could cause ports to flood, leading to delays, closures, and damage to infrastructure. Absent adaptation, permanent inundation from sea-level rise could also occur (Fleming et al. 2018). The potential economic impact of these climate stressors is significant—coastal seaports handle 99% of overseas trade in the U.S. (Jacobs et al. 2018b), and the Port of New York and New Jersey is the third-largest U.S. port by capacity (Port Authority of New York and New Jersey 2020).

Estimates of the economic damages from future delays, closures, and infrastructure damage to ports under climate change are not available, though past closures give an indication of the potential magnitude of those effects. Models for estimating the costs to retrofit existing port infrastructure and future demand for ports under climate change and global development scenarios are available in the literature and have been applied to the Port of New York and New Jersey.

3.1.1 Relevant Literature

Becker et al. (2017) modeled the costs to elevate and retrofit 100 major American coastal ports. The cost calculation model used in the study is built to be generalizable and relies on simplifying assumptions by calculating total costs per unit area for different zones of a generic model port. Additionally, note that The study's calculations are based on an adaptation response to 2 meters of sea-level rise for each port and not on a global mean sea-level rise of 2 meters, which would produce significant variability in local sea-level rise due to local geography, bathymetry, and anthropogenic subsidence. For the Port of New York and New Jersey, the researchers estimated a cost to elevate and retrofit in response to 2 meters of sea-level rise of between \$5.2 billion and \$7.1 billion. This adaptation approach is not one that could be undertaken incrementally (i.e., by elevating a few centimeters per year to keep up with annual sea-level rise), and a survey of port operators indicated 2 meters as a threshold at which adaptation is widely considered necessary (Becker et al. 2012).

Hanson and Nicholls (2020) modeled the global demand for ports using four different coupled trade/emissions scenarios and drawing on sea-level rise projections for 2050 rather than binning by sea-level rise, as done by Becker et al. (2017). Researchers projected that demand for port area will increase significantly, with 2050 demand increasing between 83% and 270% over the baseline 2010 value depending on the scenario used. The researchers stress the need for newly built, proactively adapted port infrastructure in addition to the current ports, which will require retrofitting. The study estimated a total global investment of \$223 billion to \$768 billion to meet anticipated demand in 2050, with only \$8 billion to \$18 billion allocated for the adaptation of existing ports. The authors found that adaptation of existing port areas that meet base-year trade demand represents a maximum of 6% of total port adaptation costs for all ports across the globe. Their result implies that the cost of adapting existing ports to sea-level rise is minimal in comparison to that of the need to build new port areas to accommodate increased trade demand. The need for these new port areas nonetheless offers an opportunity to build climate-resilient ports from the outset, rather than as retrofit at a later time.

The Port of New York and New Jersey sustained between \$34 million and \$52 million in infrastructure damage from Hurricane Sandy, with additional revenue losses and unquantifiable costs from delays as ships were diverted to other ports (HUD 2013). Daily import and export numbers can give some sense of the potential magnitude of the cost of port closures due to severe storms. A few studies have looked at events at the Port of New York and New Jersey and estimated total impacts, including insured losses, and the ancillary effects on economic activity associated with port closures for specific hurricane events. Table 8-12 summarizes some of these estimates. Additionally, the Port Authority of New York and New Jersey reported insured damages of \$170 million from Hurricane Sandy.⁴ These estimates for historical events provide an indication of the magnitude of disruption associated with a single storm, which could be experienced more often due to climate change.

Other impacts may be anticipated for small harbors, such as those that support commercial fishing, marinas, or other coastal commercial, industrial, or recreational activities. These medium- to small-use ports are less well-studied than larger ports, but some work is ongoing. NOAA Fisheries developed research on fishing and coastal communities with comprehensive indicators at the municipal scale as part of the Social Indicators for Coastal Communities project; the data are provided in their Indicator Map, which includes metrics such as commercial fishing engagement and vulnerability to sea-level rise and storm surge. Other ongoing research remains in progress, but includes the Port Jefferson area as part of the scope of a Comparative Assessment of Seaport Vulnerabilities to Climate Change Pilot Study for North Atlantic Medium and High-Use Seaports. These projects may provide additional information on smaller harbors and ports in New York State within the next several years.

⁴ See Smythe (2013). While financial reports report insurance receivables of over \$560 million, the Port Authority of New York and New Jersey does not distinguish between funds related to marine port infrastructure damages and those other functions (e.g., public transportation).

Table 8-12. Summary of Historical Port Closure Events and Estimated Trade Disruptions at the Port of New York and New Jersey

Source: USCG (2018),⁵. Economic impact results from IEC analysis, and with resilience results, Rose et al. (2016) and Martin Associates (2014). For results without resilience, Gordon et al. (2006) and Park (2008).

Storm	Water Level above Mean Higher High Water (m)	Sustained Wind Speed (m/s)	FEMA Public Assistance Funds (millions USD)	Closure Time (Days)	Estimated Import/ Export Disruption (millions USD)	National Economic Impact with Resilience (millions USD)	National Economic Impact without Resilience (millions USD)
Irene (2011)	1.43	20.5	\$1.64	1	\$431	\$72–\$466	\$147–\$819
Sandy (2012)	2.76	19.6	\$544	3	\$1,326	\$222–\$1432	\$451–\$2,520

3.1.2 Conclusion

Becker et al. (2017) estimated the long-term costs of retrofitting the Port of New York and New Jersey for 2 m of sea-level rise at \$5.2 billion–\$7.1 billion, and storm damage can reach tens of millions of dollars, excluding economic costs from service disruption. As flood and storm threats increase in frequency and severity under climate change, adaptation strategies may play a key role in preventing the most significant impacts. Constructing dikes and other physical barriers, relocating or elevating existing ports, and diverting ships to other ports can help mitigate losses from flooding and port closures following severe storms (Becker et al. 2017, HUD 2013).

⁵ Data for the first four columns of this table were accessed in 2018 from the U.S. Coast Guard's Homeport Internet Portal (<https://www.uscg.mil/Homeport/>). That data platform was decommissioned in April 2025, and the site now directs users to other related sites for these data. The data presented here may be available from the Port Status and Contact Information site maintained by the Coast Guard NAVCEN, although it appears that historical data may require a specialized data request.

3.2 Air Transportation

Table 8-13. Summary of Climate Change Impacts on Air Transportation

Element	Description
Description of Impacts	Air transportation infrastructure is vulnerable to essentially all primary climate stressors, with potentially significant impacts expected due to extreme weather and temperature-related impacts that could result in delays and cancellations.
Primary Climate Stressors	• Sea-level rise ◦ Rising sea level increases flood threats and may inundate airport infrastructure • Extreme weather ◦ More frequent and severe storms cause flight delays, cancellations, and structural damage • Temperature ◦ Rising temperatures reduce air density and lower maximum takeoff weights • Precipitation ◦ More frequent precipitation increases the likelihood of flight delays
Economic Values	• Cost of delays and cancellations • Cost of lost carrying capacity • Cost of infrastructure adaptation and repair (airports and aircraft)
Primary Affected Regions	Larger and busier coastal airports (e.g., New York City)
Potential Magnitude of Annual Impact in New York State	Not yet estimated, but high baseline costs of air traffic delays and potential for climate impacts suggest an impact of greater than \$100 million by end of century

Air transportation is a key sector in New York. Annually, the State’s airports serve more than 104.5 million passengers, move more than 1.5 million tons of revenue freight, and generate nearly \$100 billion in total economic impact (FAA 2020), with LaGuardia (LGA) and John F. Kennedy International (JFK) Airports accounting for more than 93 million passengers and 1.3 million tons of revenue freight annually (Port Authority of New York and New Jersey 2020).

Both airports are situated on the Atlantic Coast and are vulnerable to climate impacts, with rising sea level threatening to inundate runways and other airport infrastructure, and more frequent and severe storms expected to cause both short-term delays and cancellations as well as more lasting structural damage (Jacobs et al. 2018b, Burbidge 2016). Such disruptions would have serious costs not only for New York’s airports but also for the entire interconnected air transportation network (Jacobs et al. 2018b, Fleurquin et al. 2013, Pyrgiotis et al. 2011).

As temperatures rise, associated changes in air density are expected to result in aircraft weight restrictions, reducing carrying capacities and economic activity at airports throughout the State (Coffel and Horton 2015, Coffel et al. 2017, Jacobs et al. 2018b.).

Relevant literature assesses the expected impacts of changing climate on New York's airport infrastructure and operations and discusses potential adaptation strategies. Valuing the cost of these impacts is challenging due to the number of potential responses, though the literature does suggest approaches to valuation in some cases (e.g., cost to airlines per cancelled flight, or traveler cost of time lost to delays).

3.2.1 Relevant Literature

Coffel et al. (2017) examine the effects of changes in air density due to increasing temperatures on aircraft weight restrictions at 19 major global airports, including both LGA and JFK. As air temperature rises, air density decreases, meaning departing aircraft achieve less lift generation at a given takeoff speed and have a lower maximum takeoff weight. Combining results from model runs under both RCP4.5 and RCP8.5, the study projected a 1–10% increase in the number of flights requiring weight restrictions, with a 0.5–1.5% decrease in total payload and fuel capacity. The study finds that LGA may be particularly affected, with Boeing 737-800 and Airbus A320 (two of the five most common models in the U.S. commercial fleet) takeoffs facing weight restrictions approximately 50% of the time, with reductions in carrying capacity of nearly 3.5% and more than 2%, respectively.

An earlier study from Coffel and Horton (2015) projected weight restrictions for the Boeing 737-800 at four major U.S. airports. For LGA, the study estimated a doubling in the number of days requiring 10,000-lb weight restrictions and a large increase in the number of days requiring 15,000-lb weight restrictions.

In addition to these temperature-driven effects, impacts from rising sea levels and severe weather are projected to be significant in the State. the Regional Plan Association (2016) discussed projected impacts to LGA and JFK from sea-level rise above a 1991–2009 baseline. The report found that while JFK is unlikely to be significantly affected by even 6 feet of sea-level rise, LGA is quite vulnerable, with sea-level rise of 1 foot producing occasional high-tide flooding, 2 feet inundating some runways and terminal areas, and 3 feet permanently flooding more than half of the airport. At 6 feet of sea-level rise, LGA is

projected to be fully inundated, and JFK will be more vulnerable to storm surges from extreme weather events. Coupled with higher seas, increased precipitation and extreme weather occurrence under climate change are expected to produce delays, cancellations, and infrastructure damage (Burbidge 2016), particularly at coastal airports like LGA and JFK.

Service interruptions and delays have cascading effects on the interconnected national and international airport network on top of the local effects. The propagation of delays throughout the airport system is well-characterized both practically and theoretically (Pyrgiotis et al. 2011, Fleurquin et al. 2013). A report from the Congressional Joint Economic Committee (2008) found a national economic loss of \$40.6 billion annually from delayed flights.

3.2.2 Conclusion

The literature suggests that airport infrastructure in New York State is vulnerable to changes in all key climate indicators. more delays and cancellations are expected, and lower maximum takeoff weights may be enforced on hot days.

Adaptation strategies do exist (Transportation Research Board and the National Academies of Sciences, Engineering, and Medicine, 2015). A runway extension has been suggested, although such an approach would be challenging at JFK, LGA, and other urban airports with little space to expand (Coffel and Horton 2015). Shifting airline schedules to avoid having heavy flights take off around midday could lessen the impact of the temperature effect (Coffel et al. 2017). Shifting airline schedules to avoid having heavy flights take off around midday could lessen the impact of the temperature effect (Coffel et al. 2017). Aircraft design changes and airlines' reactions to weight restrictions (i.e., choices of whether to decrease capacity for cargo, passengers, fuel, or some combination) are difficult to predict but could shape adaptation efforts. Even with these strategies, researchers expect reductions in takeoff performance (Coffel and Horton 2015; Coffel et al. 2017).

3.3 Bridges

Table 8-14. Summary of Climate Change Impacts on Bridges

Element	Description
Description of Impacts	Increased occurrence of high-streamflow events and other extreme weather associated with climate change will increase the probability of bridge damage or failure, resulting in significant repair and delay costs.
Primary Climate Stressors	• Precipitation ○ Increased rainfall volume and intensity will damage bridge piers and decks and cause delays. • Extreme storms and weather ○ Extreme weather events may cause damage to bridges resulting in repair costs. • Sea-level rise ○ Sea-level Rise may cause damage to bridges resulting in repair costs
Economic Values	• Repair costs • Cost of travel delays
Primary Affected Regions	Statewide
Potential Annual Magnitude of Impact in New York State	Greater than \$100 million by end of century

Bridges are integral infrastructural components of New York State transportation systems. There are more than 17,000 bridges in New York State, over 50% of which are at least 75 years old (ASCE 2015). Bridge infrastructure is primarily sensitive to precipitation changes associated with climate change. In the Northeast and New York State, rainfall volume and intensity are projected to increase as climate change progresses, which will increase repair and delay costs associated with bridge scour and water overtopping decks. Sea-level rise may also cause damages to bridges with similar results.

3.3.1 Relevant Literature

Climate change effects on bridges were discussed in The Fourth National Climate Assessment with a focus on the Northeast region and the entire U.S. Sea-level rise has been associated with bridge damage and closures, especially when combined with increased storm surge during extreme weather events such as hurricanes (Jacobs et al. 2018b). Current literature does not provide state-specific estimates of bridge damage from sea-level rise. Increased precipitation and high streamflows in the Northeast worsen streambed erosion, which can cause bridge failures, lead to disruptions in transportation, and potentially cause injuries (Dupigny-Giroux et al. 2018). Strzepek et al. (forthcoming) investigate the effects of precipitation and high streamflows on bridge infrastructure in more detail and with economic impacts projected for New York State through the end of the century.

Strzepek et al. (in development) builds upon previous work on climate change and bridges from the EPA Climate Change Impacts and Risk Analysis study series (Neumann et al. 2015, EPA 2017). The methods employed by Strzepek et al. used streamflows for over 70,000 catchments across the U.S. from Wobus et al. (2017) and apply common stream-channel geometry to estimate flow velocities. The flow velocities were then used in a stressor-response relationship (known as a fragility curve) calibrated to bridge age to determine the probability of damage or failure from pier scouring (effectively undermining supports of the bridge) and deck overtopping during high flow events.

The study projects economic damages using the metrics of repair costs and the cost of travel delays during bridge outages through the twenty-first century using six Coupled Model Intercomparison Project (CMIP) 5 GCMs under two emissions scenarios (RCP4.5 and RCP8.5). Strzepek et al. (forthcoming) estimate delays using rerouting distance to the next-nearest bridge crossing, as identified in the National Bridge Inventory (DOT 2017). They define estimated damages as repair and delay costs above the baseline climate scenario (1986–2005) for 3,815 New York State bridges are summarized in Table 8-14. The estimates of annual impacts are presented below in millions of 2015 USD. The results represent the mean damage estimate across the six forecasts of future climate used in the underlying study.

The study considered two response modes:

1. Reactive response scenario, in which bridges are restored to their original condition after a damaging event
2. Proactive adaptation scenario, in which bridges are repaired to prevent damage or improve resilience at the time of the first damaging event

Table 8-15. Summary of Annual Climate Change Impacts on Bridges

Negative values represent reductions in damage relative to the modeled baseline period, reflecting fewer projected high-streamflow events that cause damage to bridge piers and overtopping.

Source: Strzepek et al. (forthcoming).

Response Scenario	Near Century (2020–2039)		Midcentury (2040–2059)		Late Century (2080–2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Reactive Response	\$106	\$100	\$96	\$83	\$165	\$158
Proactive Adaptation	\$131	\$113	\$108	\$89	\$143	\$136

By the end of the century, annual repair and delay costs associated with high streamflows were projected to exceed \$100 million under both reactive response and proactive adaptation scenarios.

3.3.2 Conclusion

Projected costs associated with high streamflows and resulting bridge damages are anticipated to be substantial in New York State. Additional costs associated with sea-level rise and extreme weather events are not quantified in the literature but may also be significant. By the end of the century, proactive adaptation is projected to save \$22 million annually under RCP8.5 compared to the reactive scenario, based on analysis from Strzepek et al. (forthcoming).

Note that New York State has updated bridge design details and permitting requirements to account for higher and faster water flow, in alignment with the provisions of the Community Risk and Resiliency Act of 2019. Bridges in the state designed since 2022 reflect these changes, which could affect the calculation of economic damages, as the underlying study used here did not account for these changes.

3.4 Subways

Table 8-16. Summary of Climate Change Impacts on Subways

Element	Description
Description of Impacts	Extreme weather, more concentrated precipitation, and increased temperatures are expected to affect communications, damaging infrastructure and increasing the frequency of service disruptions
Primary Climate Stressors	• Sea-level rise ◦ Rising sea level—inundation of coastal infrastructure, increased vulnerability to storm surge • Extreme weather ◦ More frequent and severe storms—more flooding, direct damage, and service interruptions • Temperature ◦ Rising temperatures—increased potential for electric grid overload • Precipitation ◦ More concentrated rainfall—more flooding, direct damage, and service interruptions
Economic Values	• Cost of repair • Cost of adaptation • Lost labor and productivity for riders and diverted maintenance workers • Increased morbidity and mortality risk
Primary Affected Regions	New York City urban areas
Potential Magnitude of Annual Impact in New York State	Unknown

Climate-related impacts to subways and other urban transit systems have far-reaching economic effects. With roughly 1.7 billion annual riders on the New York City subway system Metropolitan Transportation Authority (MTA) subway system in New York City (MTA 2020) and many other key sectors relying on the timely transportation of people, climate impacts on subways could be significant.

Subways are vulnerable to a range of climate stressors (MTA Climate Adaptation Task Force 2017, Mehrotra et al. 2018). Sea-level rise may lead to increased flood risk or inundation of low-elevation subway infrastructure. Data provided by the MTA as part of their recent 20-year needs assessment for 2025 to 2044 notes that over 400 miles of subway tracks in New York City are below grade and therefore are potentially exposed to flood risks (MTA, N.d). More concentrated precipitation and more intense extreme weather could produce coastal flooding due to storm surge or urban flooding due to overwhelmed stormwater control systems. Increasing temperatures could lead to heat-related grid blackouts and increased stress on systems that rely on air conditioning. Flooding and heat-related system stress could lead to delays, station closures, infrastructure damage, human health impacts, and productivity labor losses.

Projections of climate impacts on subways are lacking in the literature, though the conceptual mechanisms through which impacts are expected to occur are described, and case studies are available in New York State.

3.4.1 Relevant Literature

While subway-specific climate impact projections are not available, historical case studies do exist in New York State. No individual storm can be attributed to climate change, but with storms generally becoming more frequent and severe and sea-level rise adding to potential storm surge, studies of historical impacts can provide insight into the kinds of effects that might be expected under climate change. For example, Kaufman et al. (2012) examined the impacts of Hurricane Sandy on transportation in New York City, with a focus on public mass transit, including subways. The researchers found that costs from Hurricane Sandy were still significant, even after earlier storms prompted the City to ramp up disaster preparedness efforts. The City spent more than \$30 million on infrastructure resilience improvements in the wake of Hurricane Irene, which caused \$65 million in transportation system damage when it struck the state as a tropical storm in August 2011. Flooding from Hurricane Sandy forced the entire New York City subway system to shut down for more than two days. Commute times increased across the board, more than doubling for some, as people turned to other forms of transportation. The increased number of cars on the road produced intense gridlock, and a gas

shortage forced some to bike or walk. Notably, disadvantaged populations, including the poor and the elderly, are more vulnerable to these impacts because they disproportionately rely on public transportation services for mobility (Rosenzweig and Solecki 2014, Jacobs et al. 2018b). The Office of the New York State Comptroller estimates that the MTA set aside approximately \$7.6 billion for post-Sandy upgrades, including restoration projects (\$4.6 billion) for damaged infrastructure and new investments in resilience (\$2.6 billion) (Office of the New York State Comptroller 2022). The MTA approved a disaster recovery budget of \$10.5 billion in 2013, immediately following Hurricane Sandy (MTA Climate Adaptation Task Force 2017). Of that \$10.5 billion, roughly \$3 billion was allocated to repairing flood damage, \$5 billion went toward restoring subway assets, and the remaining \$2.5 billion was earmarked for proactive resilience projects (MTA Climate Adaptation Task Force 2017). Lost labor and productivity due to delays and potential human-health impacts from combined sewer overflow (in the event subways flood with sewage water) and decreased access to care (from service outages) are not captured in this literature, and reliable estimates are unavailable.

Notably, these kinds of impacts are not confined to 100-year events. In the summer of 2021, heavy rains from Tropical Storm Elsa flooded subways, causing delays and service interruptions (Shanahan and Wong 2021).

Heat-related stresses on the power grid could also lead to disruptions in the electricity-reliant New York City subway system (Mehrotra et al. 2018); however, projections are not currently available. Extreme heat often leads to high electricity demand overall, putting stress on the electric supply, distribution, and transmission systems, which in the worst cases can lead to power outages—which would include a loss of power to subways.

3.4.2 Conclusion

Case studies provide insight into the potential mechanisms and magnitudes of climate damage to subways, but no projections for future risk are available. Flood risk is the most significant climate stressor on subway systems and given recent history and increasing flood risk due to climate change, adaptation strategies are already being implemented in New York City subways. These approaches include installation of backup power for water pumps and charging of electric fleets, elevation and flood-proofing of existing infrastructure, use of porous pavements in flood-prone areas, and increased multimodal transportation capacity to provide redundancy (Kaufman et al. 2012, Zimmerman et al. 2014, C40 2019).

Some of these improvements to subway systems could be doubly beneficial. Increasing the efficiency and resilience of subway infrastructure has the direct effect of lowering GHG emissions, and indirectly encourages people to use mass transit, which has lower per-capita emissions than driving (MTA Climate Adaptation Task Force 2017).

3.4.3 Potential for Adaptation to Reduce Impacts

As part of its 20-year capital plan and needs assessment, the MTA has planned investments in subway resilience in three main areas:

1. Investing in flood mitigation systems, such as raised stairway landings, raised vents, and flash flood mechanical closure devices for stations most vulnerable to torrential rainfall flooding—future plans are focused on increasing pumping and water-detention capacity.
2. Beginning to design signal, switch, and rail systems to provide early warning and detection of the effects of extreme heat on the operation of these systems.
3. Adding marine doors and vent-closure devices to guard against storm-surge flooding like that experienced during Superstorm Sandy, and considering other investments as upgrades are made in the overall system (MTA, N.d., page 104).

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