INFRASTRUCTURE

10. ROADS

10.1 KEY FINDINGS

- Climate change-driven changes in temperature and precipitation are projected to result in significant impacts to U.S. roads. Discounted, reactive adaptation costs (rehabilitation measures) are estimated at $230 billion through 2100 under RCP8.5 and $150 billion under RCP4.5, on average.
- The highest per-lane-mile reactive adaptation costs are associated with impacts on paved roads due to changes in temperature and precipitation. Changes in the freeze-thaw cycle are projected to lead to a cost savings relative to the reference period.
- Across all road types and climate stressors, proactive adaptation to protect roads against climate change-related impacts is projected to decrease costs over the century by 98% under RCP8.5 and 83% under RCP4.5.

10.2 BACKGROUND

The U.S. road network is one of the nation's most important capital assets. Roads are susceptible to damage from various climate stressors, including temperature, precipitation, and flooding. Increased temperatures can cause accelerated aging of binder material and rutting of asphalt; precipitation can cause cracking and erosion; and flooding can lead to washouts and overtopping of roads. As these climate change stressors continue to change, damages to roads and costs of maintenance and repair will vary across the U.S.[208] For example, roads may experience more frequent buckling due to increased temperatures, more frequent washouts of unpaved surfaces from increased flooding, and changes in freeze-thaw cycles that cause cracking.[209]

10.3 APPROACH

The analysis estimates the costs of reactive adaptation measures resulting from climate change impacts to roads in the contiguous U.S. and evaluates the ability of proactive adaptation measures (i.e., modification of roads prior to the occurrence of climate change-related damages) to improve resiliency and reduce costs. To develop these estimates, the analysis relies on the Infrastructure Planning Support System (IPSS), a software tool that integrates stressor-response algorithms, engineering data on the U.S.

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[208] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

[209] Transportation Research Board, 2008: Potential Impacts of Climate Change on U.S. Transportation. Special Report 290, Committee on Climate Change and U.S. Transportation, National Research Council of the National Academies.

road network, and the climate projections described in the Modeling Framework section of this Technical Report.[210,211] The IPSS tool estimates the potential impacts related to three climate stressors (temperature, precipitation,[212] and timing of freeze-thaw cycles[213]) for three road types (paved, unpaved, and gravel), as summarized in Table 10.1, and quantifies the costs of reactive adaptation in the form of maintenance activities required to ensure current levels of service.[214] These costs represent the incremental change in expenditures associated with projected climate change relative to the reference period (1950-2013) as modeled by the five GCMs under RCP8.5 and RCP4.5. In addition, many parts of the U.S. road network are under-maintained today, which can increase their vulnerability to climate change. This analysis focuses on the additional impacts due to climate change independent of this underlying vulnerability.

The IPSS tool also quantifies the costs of proactive adaptation measures to protect and rehabilitate roads against impacts caused by climate stressors, where applicable. The differences between the costs of proactive adaptation measures and the costs of reactive adaptation measures to address climate change-related impacts represent the effects of proactive adaptation for the roads sector.[215] For more information on the approach, please refer to Chinowsky and Arndt (2012), Espinet et al. (2016), and Neumann et al. (2014).[216,217,218]

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[210] Schweikert, A., P. Chinowsky, X. Espinet, and M. Tarbert, 2014: Climate change and infrastructure impacts: comparing the impact on roads in ten countries through 2100. *Procedia Engineering*, **78**, 306-316.

[211] Chinowsky, P., A. Schweikert, G. Hughes, C.S. Hayles, N. Strzepek, K. Strzepek, and M. Westphal, 2015: The impact of climate change on road and building infrastructure: a four-country study. *International Journal of Disaster Resilience in the Built Environment*, **6**, 382-396.

[212] The hydrologic movement of water across a road surface, also known as overtopping due to a flooded waterway, is not directly modeled in this analysis.

[213] Freeze-thaw related impacts affect the sub-surface components of roads while temperature-related damage is limited to the surface.

[214] To maintain service, the level of maintenance applied can vary over time, and can therefore be larger or smaller than the historic level from the reference period.

[215] The analysis assumes that for a given climate stressor, proactive adaptation prevents the need for future climate-induced maintenance.

[216] Chinowsky, P. and C. Arndt, 2012: Climate Change and Roads: A Dynamic Stressor–Response Model. *Review of Development Economics*, **16**, 448-462.

[217] Espinet, X., A. Schweikert, N. van den Heever, and P. Chinowsky, 2016: Planning resilient roads for the future environment and climate change: quantifying the vulnerability of the primary transport infrastructure system in Mexico. *Transport Policy*, **50**, 78-86.

[218] Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change,* **131**, 97-109.

Table 10.1. Summary of Modeled Damages and Proactive Adaptation Measures for U.S. Roads

Climate Stressor	Road Type	Impacts	Response Measures
Temperature	Paved	Surface degradation and increased roughness due to thermal cracking and rutting.	Change asphalt mix to include binder with appropriate temperature performance.
	Unpaved	Not Modeled*	N/A
	Gravel	Not Modeled*	N/A
Precipitation	Paved	Erosion of base and sub-base due to infiltration as well as increased cracking.	Modify binder/sealant application and increase depth of base layer.
	Unpaved	Erosion of surface and development of rutting.	Upgrade to gravel or paved road.^
	Gravel	Erosion of base due to subsidence resulting in uneven surface.	Increase thickness of gravel and sub-base to improve strength and allow for better drainage.
Freeze-Thaw	Paved	Degradation of base layer due to soil heaving, and increased surface damage due to settling and movement.	Modify design to increase surface density and reduce infiltration.
	Unpaved	Not Modeled*	N/A
	Gravel	Not Modeled*	N/A

*The effects of the temperature and freeze-thaw climate stressors on gravel and unpaved roads are likely inconsequential and are therefore not modeled.

^While the accepted method for adapting unpaved roads is to upgrade to a paved surface, newer and potentially less-costly approaches exists that are not widely established, and therefore not included in the modeling.

10.4 RESULTS

Through the end of the century, climate change is projected to result in $230 billion and $150 billion in reactive adaptation costs to U.S. roads under RCP8.5 and RCP4.5, respectively (2015-2099, $2015, discounted at 3%, five-GCM average). Across the five climate models, cumulative costs range from $59 to $530 billion under RCP8.5 and from $75 to $350 billion under RCP4.5. The largest impacts are estimated under the HadGEM2-ES model, which are the hottest climate projections analyzed, while the smallest impacts are seen under the coolest model, GISS-E2-R. As shown in Table 10.2, reactive adaptation costs are dominated by paved roads and are higher under RCP8.5 than under RCP4.5 in all but one of the five models (GISS-E2-R). On a per-lane-mile basis, projected costs are highest for paved roads ($37,000 under RCP8.5 and $24,000 under RCP4.5), followed by gravel roads ($4,500 under RCP8.5 and $3,800 under RCP4.5) and unpaved roads ($2,200 under RCP8.5 and $1,800 under RCP4.5).

Table 10.2. Cumulative Change in Reactive Adaptation Costs

The table presents the estimated change in reactive adaptation costs for the period 2015-2099 relative to the reference period (1950-2013) (billions $2015, discounted at 3%, five-GCM average).

GCM	Road Type	RCP8.5	RCP4.5
CanESM2	Paved	$160	$67
	Gravel	$7.7	$5.0
	Unpaved	$3.7	$2.4
	TOTAL	**$170**	**$75**
CCSM4	Paved	$240	$150
	Gravel	$2.9	$1.7
	Unpaved	$1.4	$0.9
	TOTAL	**$250**	**$150**
GISS-E2-R	Paved	$50	$74
	Gravel	$6.4	$8.0
	Unpaved	$3.1	$3.9
	TOTAL	**$59**	**$86**
HadGEM2-ES	Paved	$510	$340
	Gravel	$9.4	$9.1
	Unpaved	$4.5	$4.4
	TOTAL	**$530**	**$350**
MIROC5	Paved	$120	$74
	Gravel	$3.5	$1.1
	Unpaved	$1.7	$0.6
	TOTAL	**$130**	**$75**
5-GCM Average	**Paved**	**$220**	**$140**
	Gravel	**$6.0**	**$5.0**
	Unpaved	**$2.9**	**$2.4**
	TOTAL	**$230**	**$150**

Figure 10.1 presents the estimated annual per-lane-mile reactive adaptation costs in 2050 and 2090 at the regional level, broken down by climate stressor and RCP. Temperature-related impacts dominate in all regions, particularly in the Northeast, Southeast, and Midwest, and are consistently higher under RCP8.5 compared to RCP4.5. Impacts related to precipitation are smaller, but generally increase from 2050 to 2090. Partially offsetting these impacts, the freeze-thaw stressor is projected to result in negative costs (savings) compared to the reference period in all regions and under all scenarios. This is

due to the projected shift in freeze zone status for a large portion of the country, from moderate-freeze to no-freeze zones. The shift in these areas significantly reduces the maintenance costs for freeze-thaw costs relative to the reference period. As shown in Figure 10.1, these savings are projected to be particularly high in the Northeast. Although not shown in the figure, the largest total reactive adaptation costs are projected to occur in the Southeast and Midwest, which is partially due to the comparatively higher number of lane miles in these regions and also to greater climate stress.

Figure 10.1. Change in Annual Per-Lane-Mile Reactive Adaptation Costs

The graphs show changes in reactive adaptation costs in 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1950-2013). Results represent the five-GCM average and are presented in thousands of $2015, undiscounted.

Potential for Adaptation to Reduce Impacts

Table 10.3 presents the cumulative change in costs for 2015-2099 relative to reference period (1950-2013) with reactive and proactive adaptation. Across all stressors and road types, proactive adaptation is projected to decrease costs by 98% under RCP8.5 and 83% under RCP4.5 relative to the scenario with reactive adaptation. For paved roads, proactive adaptation reduces temperature-related costs by 68% and 59% under RCP8.5 and RCP4.5, respectively, and reduces precipitation-related costs by 58% and 47%, respectively. For gravel and unpaved roads, precipitation-related costs are higher with proactive adaptation than with reactive adaptation. This is because the options for proactively adapting unpaved roads to increased precipitation risks are limited to upgrading the roads to paved or gravel, which are both very expensive. Proactive adaptation for gravel roads is also very expensive, as it essentially involves reconstructing the road with enhanced structural capacity. Costs associated with the freeze-thaw stressor do not change significantly between the reactive and proactive adaptation scenarios. In the proactive adaptation scenario, total, cumulative, discounted costs are higher under RCP4.5 than under RCP8.5 because the freeze-thaw related savings are greater under RCP8.5.

Table 10.3. Cumulative Change in Costs with Reactive and Proactive Adaptation

The table presents cumulative change in costs with reactive and proactive adaptation for the 2015-2099 period relative to the reference period (1950-2013) in billions $2015, discounted at 3%, for the five-GCM average.

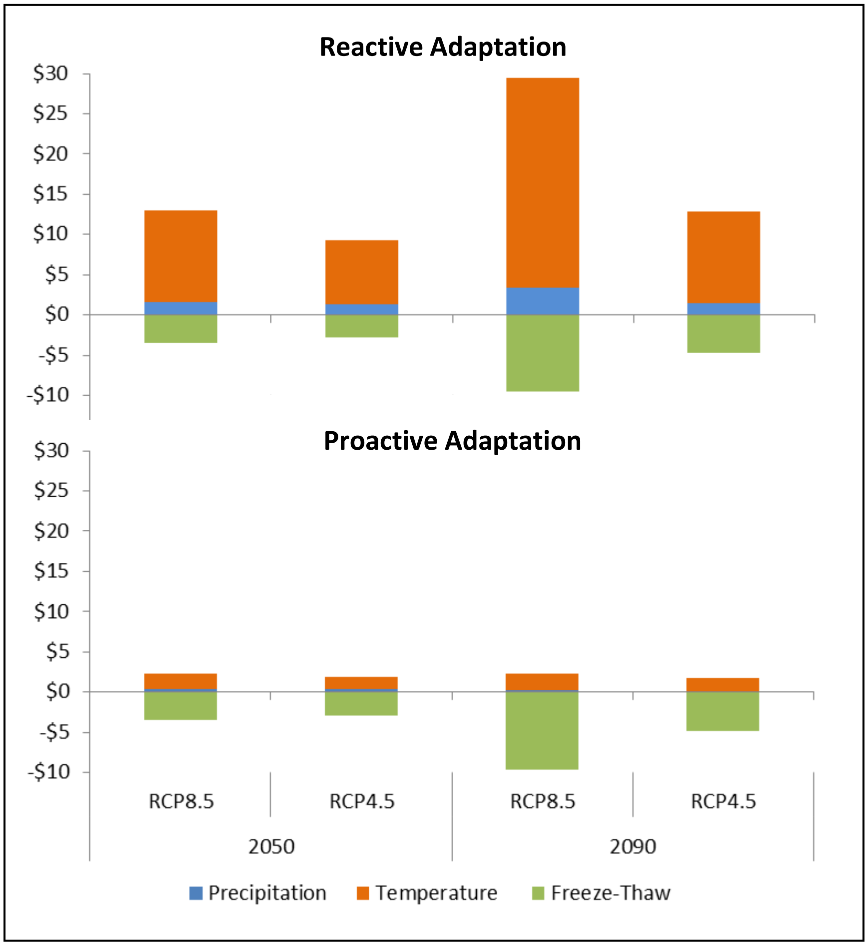
	RCP8.5		RCP4.5	
	Reactive Adaptation	Proactive Adaptation	Reactive Adaptation	Proactive Adaptation
Temperature				
Paved	$300	$95	$190	$78
Gravel	N/A*	N/A*	N/A*	N/A*
Unpaved	N/A*	N/A*	N/A*	N/A*
Subtotal	**$300**	**$95**	**$190**	**$78**
Freeze-Thaw				
Paved	-$120	-$120	-$77	-$80
Gravel	N/A*	N/A*	N/A*	N/A*
Unpaved	N/A*	N/A*	N/A*	N/A*
Subtotal	**-$120**	**-$120**	**-$77**	**-$80**
Precipitation				
Paved	$37	$15	$30	$16
Gravel	$6	$7	$5	$6
Unpaved	$3	$6	$2	$6
Subtotal	**$46**	**$28**	**$37**	**$28**
Total				
Paved	$220	-$8	$140	$14
Gravel	$6	$7	$5	$6
Unpaved	$3	$6	$2	$6
TOTAL	**$230**	**$5**	**$150**	**$26**

*The effects of the temperature and freeze-thaw climate stressors on gravel and unpaved roads are likely inconsequential and are therefore not modeled.

Figure 10.2 shows the change in total projected costs in 2050 and 2090 relative to the reference period with reactive and proactive adaptation, distributed across climate stressors. Temperature- and precipitation-related costs are significantly reduced in the proactive adaptation scenario relative to the reactive adaptation scenario, while freeze-thaw related savings do not change significantly between the two scenarios.

Figure 10.2. Change in Annual Costs for U.S. Roads with Reactive and Proactive Adaptation

The graphs present the change in annual costs for reactive and proactive adaptation in 2050 (2040-2059) and 2090 (2080-2099) relative to the historic reference period (1950-2013) in billions $2015, undiscounted, for the five-GCM averages.



10.5 DISCUSSION

The analysis estimates that climate change will result in increased costs of maintaining, repairing, and replacing roads, which is consistent with the findings of the assessment literature.[219] In particular, the analysis projects high costs associated with temperature- and precipitation-related impacts to paved roads. Total annual costs in 2090 are estimated at $20 billion under RCP8.5 and $8.1 billion under RCP4.5 ($2015, undiscounted, five-GCM average). With well-timed proactive adaptation, the analysis projects savings of $7.3 billion under RCP8.5 and $3 billion under RCP4.5 compared to the reference period. A previous study using a similar approach and different climate scenarios found that the estimated costs through 2100 were $10 billion under a high emissions scenario and $2.6 billion under a

[219] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

global GHG mitigation scenario (discounted at 3%).[220] The difference between the current results and these previous estimates reflect two key differences between the two analyses. First, the savings reflected in the current results are due to the changes in the freeze-thaw stressor, as described above, which were modeled differently in the previous analysis. Second, the climate models used in the previous analysis project significantly wetter conditions across the U.S. compared to the models used in the current analysis, resulting in larger precipitation-related costs for unpaved roads.

The large reductions in costs due to proactive adaptation in this study are estimated under a scenario assuming well-timed and effective adaptation. As described in the Approach section, examples of proactive adaptation strategies include changing asphalt mixes to use binders with better temperature performance, or using gravel on unpaved roads that are subject to increasingly heavy precipitation. This proactive scenario is useful for evaluating how costs related to climate change impacts could be reduced. It is worthwhile to note, however, that the timing of road maintenance is important, and delays or deferred maintenance can decrease the potential effectiveness of adaptation, yielding smaller reductions in total costs than those reported under the proactive adaptation scenario which assumes well-timed investments to maintain levels of service.

Implementation of well-timed adaptation measures to maintain service levels is a potentially overly optimistic assumption given that infrastructure investments are oftentimes delayed and underfunded. Significant cases of delayed maintenance can result in road closure, which would lead to large public costs (e.g., increased travel time) not reported here. In addition, for unpaved roads, the effects of changes in precipitation are likely dependent on the amount of traffic on the road, which is not explicitly captured in the analysis. However, advancements in technology and changes in driving behavior are not directly modeled in the analysis, and could have long-term implications on the vulnerability of the road network to climate change. Lastly, among the three climate stressors examined in the analysis, freeze-thaw is the most complex and the most uncertain. The analysis assumes that areas fall neatly into climate zones with specific freeze-thaw risks (i.e., no-freeze or moderate-freeze) and that road maintenance decisions are made accordingly. In reality, areas that are close to the border between no-freeze and moderate-freeze zones will need to manage for some freeze events, which would lead to larger costs than those reported here. Specifically, there is a 61-70% increase in maintenance costs from no-freeze zones to moderate-freeze zones, so the cost for no-freeze zones can increase quickly if freeze events do in fact occur.

[220] EPA, 2015: Climate Change in the United States: Benefits of Global Action. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.

11. BRIDGES

11.1 KEY FINDINGS

- By 2050, an estimated 4,600 inland bridges across the contiguous U.S. are projected to become vulnerable each year under RCP8.5. Under RCP4.5, this estimate is reduced to 2,500. By 2090, 6,000 bridges are projected to become vulnerable each year under RCP8.5, while 5,000 would be vulnerable under RCP4.5.
- National average annual proactive maintenance or rehabilitation costs under RCP8.5 are estimated at $1.7 billion by 2050 and $1.0 billion by 2090. Costs are reduced under RCP4.5 to $1.5 billion each year in 2050 and $510 million each year in 2090.

11.2 INTRODUCTION

Road bridges are a central component of the U.S. transportation system. With the average U.S. bridge now over 40 years old, however, vehicles cross structurally deficient bridges over 2 million times a day.[221] Similar to other transportation infrastructure, bridges are vulnerable to a range of threats from climate change.[222] Currently, most bridge failures caused by extreme events are due to scour, where swiftly moving water removes sediment from around bridge structural supports, weakening or destroying their foundations.[223] Increased flooding and long-term river flow changes caused by climate change are expected to increase the frequency of bridge scour, further stressing the aging U.S. transportation system.

11.3 APPROACH

The analysis estimates impacts on inland bridges that span bodies of water in the contiguous U.S. resulting from projected changes in peak flows from 100-year, 24-hour precipitation events in two future eras: 2050 (2035-2064) and 2090 (2070-2099),[224] as modeled by five GCMs under RCP8.5 and RCP4.5. Using data from the National Bridge Inventory, this method quantifies the costs associated with two levels of perfect-foresight responses for bridges determined to be vulnerable as a result of climate change: (1) the application of riprap to stabilize bridges, and (2) the strengthening of bridge piers and abutments with additional concrete. The analysis assumes that riprap is required when projected peak flows from a 100-year, 24-hour storm increase by 20%. Concrete strengthening is required when peak flows increase by 60% for bridges on non-sandy soils and by 100% for bridges on sandy soils. This study requires an estimate of peak flows from rainfall events and simulation of nonlinear watershed processes, accounting for watershed land use, soil type, and topography. The method adopted is the

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[221] DOT, cited 2017: National Bridge Inventory. United States Department of Transportation, Federal Highway Administration. Available online at https://www.fhwa.dot.gov/bridge/nbi.cfm

[222] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

[223] Briaud J.L., Hunt B.E. (2006) Bridge scour and the structural engineer. Structure December:58–61.

[224] The era referred to as 2090 is not centered on 2090 because the climate data was only available through 2099 and therefore the 30-year period required for the analysis had to begin in 2070.

U.S. Department of Agriculture's Natural Resources Conservation Service TR-20 model, used to convert 24-hour rainfall "design-storm" depths to peak flows, consistent with Wright et al. (2012).[225,226]

Based on the projections of bridge vulnerability, the analysis evaluates a response scenario in which bridges are proactively rehabilitated to avoid service disruption caused by climate-induced changes in extreme river flow.[227] Projected costs in this scenario include the costs of riprap installation and concrete strengthening based on engineering data from the reference period. Importantly, this analysis assumes perfect foresight, in that bridges are only rehabilitated if they are known to be threatened by a near-term river flow level that crosses one of the thresholds described above. This scenario may underestimate potential bridge damages, as the costs of proactive, well-timed rehabilitation are likely far lower than the costs associated with repairing or reconstructing bridge failures, and because this analysis does not estimate the damages associated with delays or disruption from loss of use. Also, this analysis focuses on the incremental effects due to climate change, and does not estimate the additional costs associated with retrofitting bridges that were structurally vulnerable in the reference period (i.e., there may be deficient bridges that are not projected to be rehabilitated because the climate projections do not suggest that they will be subjected to damaging high river flows).

For more information on the CIRA approach and results for the bridges sector, please refer to Neumann et al. (2014)[228] and Wright et al. (2012).[229]

11.4 RESULTS

Figure 11.1 shows the estimated percentage of bridges identified as vulnerable to climate change in each four-digit HUC of the contiguous U.S. In 2050 (2035-2064), the majority of HUCs across the U.S. are projected to contain 20% or fewer vulnerable bridges under both RCPs. By 2090 (2070-2099), there are a greater number of HUCs with 40% or more vulnerable bridges, particularly under RCP8.5. Table 11.2 summarizes the annual numbers of vulnerable bridges by region. By 2050, approximately 4,600 bridges are projected to be vulnerable each year under RCP8.5.[230] Under RCP4.5, this number is reduced by 46% to 2,500. Under both RCPs, the Southeast is projected to experience the highest number of vulnerable bridges in 2050, followed by the Midwest. By 2090, 6,000 bridges are projected to be vulnerable each year under RCP8.5, and this number is reduced to 5,000 per year under RCP4.5.[231] The Midwest is projected to experience the highest number of vulnerable bridges in 2090 under both RCPs.

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[225] Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J. Smith, J. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, **17**, 939-955, doi: 10.1007/s11027-011-9354-2.

[226] For this analysis, the ratio of peak precipitation that is used as an input to TR-20 is slightly different than past applications; it reflects identification of a 100-yr, 24-hour storm over a longer period (1980-2009; 30 years rather than 20 years) and also by fitting an extreme value Type 1 (Gumbel) distribution to the 30 year set of annual maximum precipitation values. The use of an extreme value Type 1 distribution differs from past applications, such as Wright et al. (2012), which have used the Log Pearson Type III distribution. The update in method for identifying the 100-year 24-hr precipitation event in each HUC reflects a desire to better match, and to not statistically overfit, the statistical characteristics of the precipitation distributions.

[227] Bridge overtopping, whereby extreme river flows rise higher than bridge decks, are an important effect not directly modeled in this analysis.

[228] Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to U.S. infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, **131**, 97-109, doi: 10.1007/s10584-013-1037-4.

[229] Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J. Smith, J. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, **17**, 939-955, doi: 10.1007/s11027-011-9354-2.

[230] Across the contiguous U.S., the analysis models impacts on a total of 440,000 bridges.

[231] The same bridge may be considered vulnerable in both 2050 and 2090; for example, a bridge may be subject to peak flows that surpass the threshold for riprap strengthening in 2050, and then in 2090 it may become subject to peak flows surpassing the threshold for concrete strengthening.

Figure 11.1. Percentage of Bridges Identified as Vulnerable to Climate Change

Estimated percentage of bridges in each four-digit HUC of the contiguous U.S. identified as vulnerable under each RCP in 2050 (2035-2064) and 2090 (2070-2099).

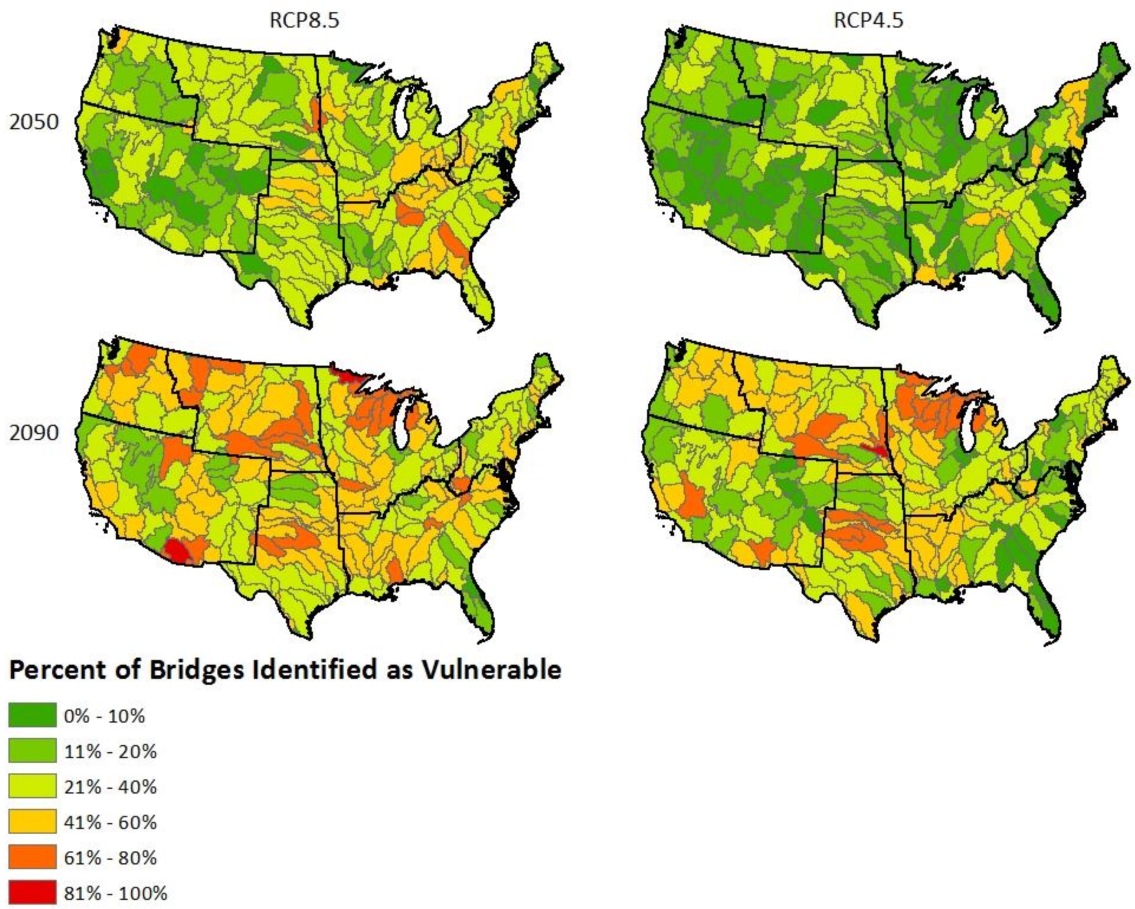

Table 11.1. Projected Number of Vulnerable Bridges per Year

Estimated number of bridges in each region identified as vulnerable each year by 2050 (2035-2064) and 2090 (2070-2099) under each RCP. Values represent averages of the five GCMs. Totals may not sum due to rounding.

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	510	350	570	390
Southeast	1,400	750	1,600	1,200
Midwest	1,300	600	1,700	1,500
Northern Plains	260	160	410	430
Southern Plains	810	420	1,100	1,000
Southwest	160	120	360	260
Northwest	120	83	200	160
National Total	**4,600**	**2,500**	**6,000**	**5,000**

Table 11.2 presents the average proactive maintenance costs in 2050 and 2090. For the five-GCM average, annual costs under RCP8.5 are estimated at $1.7 billion by 2050 and $1.0 billion by 2090. Projected annual costs are reduced under RCP4.5 to $1.5 billion in 2050 and $510 million in 2090. Costs are smaller in 2090 than in 2050 under both RCPs because many bridges require repairs due to climate changes by 2050, and once repaired, are less susceptible to extreme river flow impacts in 2090. Of the five GCMs, GISS-E2-R, HadGEM2-ES, and MIROC5 project the highest impacts and CCSM4 projects the lowest impacts.

Table 11.2. Projected Proactive Maintenance Costs to U.S. Bridges Across Climate Models

Average annual costs (millions) in the contiguous U.S. in 2050 (2035-2064) and 2090 (2070-2099) (undiscounted, $2015).

GCM	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$1,700	$1,500	$1,100	$560
CCSM4	$950	$1,100	$670	$310
GISS-E2-R	$1,500	$1,500	$1,300	$390
HadGEM2-ES	$2,000	$1,700	$1,100	$740
MIROC5	$2,200	$1,600	$800	$530
5-GCM Average	**$1,700**	**$1,500**	**$1,000**	**$510**

Table 11.3 presents the estimated proactive maintenance costs at national and regional levels. At a national scale, projected proactive maintenance costs under RCP8.5 are estimated at $1.4 billion per year by 2050 and $1.1 billion by 2090, while under RCP4.5 costs are reduced to $1.2 billion per year by 2050 and $590 million by 2090. The Midwest and the Southeast incur the highest adaptation costs to maintain bridge service in both eras under both RCPs. Proactive maintenance costs are projected to be the smallest in the Northern Plains and Northwest, mostly due to the smaller number of bridges in those regions. Across the majority of regions, impacts are reduced under RCP4.5 relative to RCP8.5 (Table 11.3).

Table 11.3. Regional Proactive Maintenance Costs for Vulnerable Bridges

Average annual costs (millions) by region in 2050 (2035-2064) and 2090 (2070-2099) for the five-GCM average (undiscounted, $2015).

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	$220	$180	$120	$77
Southeast	$430	$340	$300	$150
Midwest	$430	$390	$270	$110
Northern Plains	$89	$91	$42	$25
Southern Plains	$300	$300	$180	$83
Southwest	$120	$95	$54	$37
Northwest	$83	$71	$31	$22
National Total	**$1,700**	**$1,500**	**$1,000**	**$510**

11.5 DISCUSSION

The findings regarding near-term bridge vulnerability and proactive maintenance costs due to unmitigated climate change are consistent with the findings of the assessment literature,[232] but this work provides quantification of those risks in a consistent manner for a full lower 48 state domain. It is important to consider several limitations of the analysis. The analysis considers the effects of climate change on inland bridges, not coastal bridges, and also focuses only on high streamflow risks, and not other climatic stresses (e.g., extreme temperature) or synergistic effects of climate with other stresses, and therefore is likely an underestimate of future impacts of climate change on the nation's total bridge inventory. In addition, although there will likely be significant changes to the nation's bridges over the course of the century—some bridges will be strengthened for reasons separate from climate change risks, some will deteriorate, some will be removed, and new bridges will be added—this analysis estimates costs based on the existing bridge inventory in its current state. Further, this analysis assumes that proactive, well-timed adaptation will be taken to maintain the current level of bridge service. In reality, some bridges will likely fail in the future due to a combination of delayed maintenance and inadequate design to address future climate risks, resulting in loss of use and the associated public costs,

[232] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

such as increased traffic and delays. Finally, the adaptation option evaluated here only consider a class of actions that could reduce physical impacts at the bridge facility. Other adaptation options to reduce the consequences of those physical impacts – such as re-routing of road traffic or building in other forms of network flexibility – could also be considered, and might in some cases be more cost-effective than bridge strengthening.

12. RAIL

12.1 KEY FINDINGS

- Increasing temperatures are projected to result in significant damages to the U.S. rail system. In response to increased risks of rail cracking, rail operators will be forced to reduce speeds, causing economic damages associated with delays to freight and passenger rail. Average cumulative discounted damages through 2100 are estimated at $50 billion under RCP8.5 and $40 billion under RCP4.5.
- Well-timed proactive adaptation is projected to reduce average cumulative discounted costs through 2100 to $12 billion under RCP8.5 and $4.5 billion under RCP4.5.

12.2 BACKGROUND

The U.S. rail network is a critical component of the nation's infrastructure system, connecting U.S. consumers with agricultural, economic, logistics, and manufacturing centers across the nation and the world.[233] Climate change affects the rail network principally through projected temperature increases across the U.S. Passenger and freight tracks are susceptible to damage during periods of extreme heat, which are expected to increase in frequency as a result of climate change. Specifically, when exposed to temperatures outside of the range of normal operating conditions, steel rail expands and can undergo a displacement or buckling called a "sun kink," increasing the risk of derailments and leading to costly maintenance expenditures and train delays.

12.3 APPROACH

The purpose of the analysis it to determine the potential risk of climate change to the Class I rail network in the U.S., which comprises 140,000 rail miles operated by seven railroad companies and carrying both freight and passenger trains.[234] To model the existing rail network, the analysis relies on geospatial data from the National Transportation Atlas Database (NTAD) for active main line and sub main line track.[235] Average daily train traffic volume is estimated based on highway-rail crossing data from the Federal Railroad Administration's (FRA's) Office of Safety Analysis.[236,237]

The analysis uses the Infrastructure Planning Support System (IPSS) tool, which incorporates engineering knowledge, stressor-response algorithms, and climate projections, to quantify potential vulnerabilities to the rail system resulting from climate change.[238] The tool quantifies the costs of reactive adaptation and proactive adaptation under RCP8.5 and RCP4.5 and for each of the five GCMs, and represent impacts above and beyond what is spent on periodic maintenance. The reactive adaptation costs are

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[233] DOT, cited 2016: Freight Rail Overview. United States Department of Transportation, Federal Railroad Administration. Available online at https://www.fra.dot.gov/Page/P0528

[234] DOT, cited 2016: Freight Rail Today. United States Department of Transportation, Federal Railroad Administration. Available online at https://www.fra.dot.gov/Page/P0362

[235] DOT, cited 2016: Bureau of Transportation Statistics: National Transportation Atlas Databases 2015. [Available online at: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/2015/index.html]

[236] FRA's Office of Safety Analysis provides data on daily highway-rail crossings for over 150,000 unique highway-rail crossings. Based on these data, the study estimated the average daily volume of train traffic per grid cell.

[237] DOT, cited 2016: Highway-Rail Crossings. United States Department of Transportation, Federal Railroad Administration, Office of Safety Analysis. Available online at http://safetydata.fra.dot.gov/OfficeofSafety/publicsite/Query/gxrtally1.aspx

[238] Chinowsky, P., and C. Arndt, 2012: Climate change and roads: a dynamic stressor-response model. *Review of Development Economics*, **16**, 448-462, doi: 10.1111/j.1467-9361.2012.00673.x

associated with delays resulting from increased temperatures under climate change, as current rail safety guidelines require reduced speed and traffic in areas where extreme temperatures are occurring or predicted. Delays are first quantified in minutes and then converted to dollars using a methodology that estimates the cost of delays for freight trains to the railroad company and the public.[239] The costs of delays include costs to the railroad companies (including the costs of crew, cars, locomotives, lading, and fuel), and costs to the public include costs of locomotive emissions attributed to additional operational time and car traffic delay at railroad crossings.[240]

The study also quantifies the costs of proactive adaptation measures that reduce the risk of rail line damage and the associated temperature-based delays.[241] The proactive adaptation measure modeled is the FRA-proposed installation and use of temperature sensors to identify the times and locations when speed and traffic reductions are required due to local conditions.[242] This is in contrast to the current practice of widespread restrictions over a predetermined number of hours, which corresponds to a broader set of delays. For more information on the approach to estimating impacts on rail infrastructure, please see Chinowsky et al. (2017).[243]

12.4 RESULTS

The projected cumulative reactive adaptation costs to the U.S. rail network are substantial, estimated at $50 billion under RCP8.5 and $40 billion under RCP4.5 for the five-GCM average (2016-2099, $2015, discounted at 3%). Table 12.1 shows the projected annual reactive adaptation costs for 2050 and 2090 for the five GCMs and the five-GCM average. As shown, costs are consistently higher in 2090 than in 2050 under both RCPs and across all five models. For the five-GCM average, annual costs in 2090 are $5.5 billion and $3.5 billion (undiscounted $2015) under RCP8.5 and RCP4.5, respectively. Projected costs are largest under the HadGEM2-ES model and smallest under the GISS-E2-R model, which, respectively, represent the hottest and coolest GCMs of the five analyzed.

[239] Lovett, A.H., C.T. Dick, and C.P. Barkan, 2015: Determining freight train delay costs on railroad lines in North America. In: Proceedings of the International Association of Railway Operations Research (IAROR) 6th International Conference on Railway Operations Modelling and Analysis, Tokyo, Japan. Available online at http://railtec.illinois.edu/articles/Files/Conference%20Proceedings/2015/Lovett-et-al-2015-IAROR.pdf

[240] The analysis quantifies the costs of conventional pollutants excluding CO_2.

[241] In this scenario with proactive adaptation, impacts include both the costs of the adaptation measure as well as any damages resulting from climate change that are not prevented by proactive adaptation.

[242] Kish, A. and G. Samavedam, 2013: Track Buckling Prevention: Theory, Safety Concepts, and Applications. United States Department of Transportation, Federal Railroad Administration. Technical Report No. DOT/FRA/ORD-13/16. Available online at https://www.fra.dot.gov/eLib/details/L04421

[243] Chinowsky, P., J. Helman, S. Gulati, J. Neumann, and J. Martinich, 2017: Impacts of Climate Change on Operation of the US Rail Network. *Transport Policy*. doi: 10.1016/j.tranpol.2017.05.007.

Table 12.1. Projected Annual Reactive Adaptation Costs to the U.S. Rail System

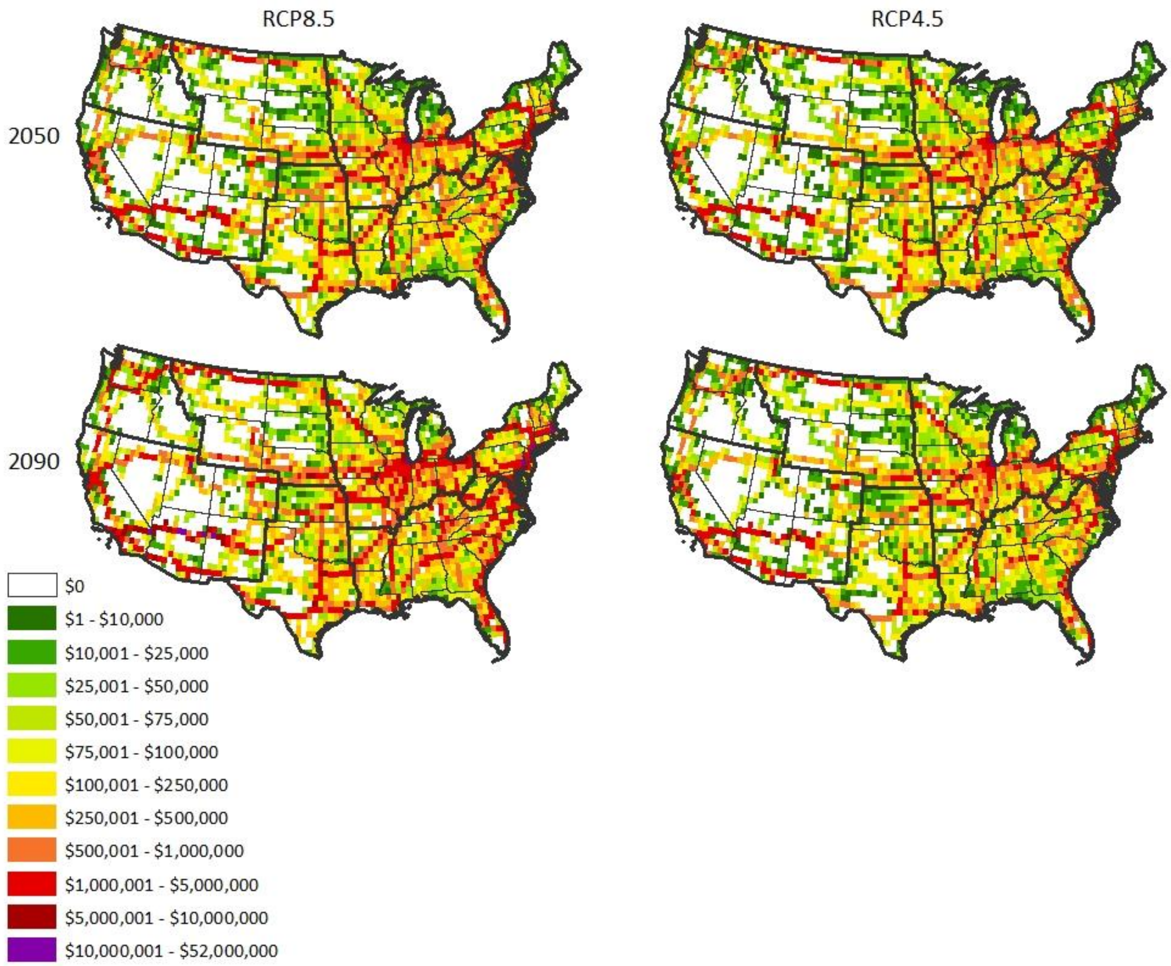
The table presents the change in reactive adaptation costs in 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1950-2013) (billions $2015, undiscounted).

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$1.9	$1.6	$6.1	$3.8
CCSM4	$1.7	$1.3	$5.1	$3.2
GISS-E2-R	$1.3	$1.1	$4.0	$2.4
HadGEM2-ES	$2.2	$1.8	$6.6	$4.4
MIROC5	$1.6	$1.6	$5.8	$3.7
5-GCM Average	**$1.8**	**$1.5**	**$5.5**	**$3.5**

Figure 12.1 displays the average annual reactive adaptation costs in 2050 and 2090 under both RCPs at the half-degree grid cell level (approximately 34 square miles). The white areas in the maps represent areas where no Class I rail is present in addition to where the costs of climate change are estimated to be near zero. The highest projected costs are mainly concentrated in the Northeast, Midwest, and Southwest, particularly under RCP8.5. These impacts are due to the relatively higher rail network density and/or the projected increases in temperature relative to the temperature at which the rails were designed to operate.

Figure 12.1. Average Annual Reactive Adaptation Costs to the U.S. Rail Network

The maps display the change in reactive adaptation costs relative to the reference period (1950-2013) for the five-GCM average ($2015, undiscounted) in 2050 (2040-2059) and 2090 (2080-2099).



Potential for Proactive Adaptation to Reduce Impacts

As described in the Approach section, the analysis also quantifies the impacts of climate change on the rail system in a scenario where proactive adaptation measures are implemented to reduce the temperature-delay effect on the rail system. Table 12.2 shows the estimated cumulative costs of climate change by region with reactive and proactive adaptation.[244] As shown, impacts are reduced significantly at the national level when proactive adaptation measures are taken. For the five-GCM average, estimated cumulative costs are reduced from $50 billion to $12 billion (77%) under RCP8.5 and from $40 billion to $4.5 billion (89%) under RCP4.5, for savings of $39 billion and $35 billion, respectively. At the regional level, reactive adaptation costs are highest in the Southeast and Southern Plains under both

[244] As described in the Approach section, impacts in the scenario with proactive adaptation include both the costs of making proactive adaptation measures and the climate-change related damages that are not prevented by the modeled adaptation.

RCPs. Proactive adaptation reduces these costs by 73% and 79%, respectively, under RCP8.5 and by 84% and 91%, respectively, under RCP4.5.

Table 12.2. Projected Cumulative Costs to U.S. Rail with Reactive and Proactive Adaptation

The table presents the cumulative reactive and proactive adaptation costs to the U.S. rail system by region for the period 2016-2099 relative to the reference period (five-GCM average, billions $2015, discounted at 3%).

	Total Costs (Billions $2015)		Costs Per Rail Mile (Thousands $2015)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Reactive Adaptation				
Northeast	$8.7	$7.1	$410	$330
Southeast	$10	$7.7	$260	$200
Midwest	$4.6	$3.6	$100	$78
Northern Plains	$1.4	$1.0	$85	$62
Southern Plains	$14	$11	$620	$500
Southwest	$6.5	$5.2	$170	$130
Northwest	$5.2	$4.1	$600	$470
National Total	**$50**	**$40**	**$290**	**$230**
Proactive Adaptation				
Northeast	$1.6	$0.55	$77	$26
Southeast	$2.8	$1.2	$72	$31
Midwest	$0.63	$0.24	$14	$5
Northern Plains	$0.53	$0.23	$33	$14
Southern Plains	$2.9	$1.0	$130	$44
Southwest	$1.4	$0.60	$72	$30
Northwest	$1.6	$0.72	$180	$82
National Total	**$12**	**$4.5**	**$67**	**$26**

12.5 DISCUSSION

This analysis projects significant costs for the U.S. rail system associated with both reactive adaptation to increasing temperatures under climate change, which is consistent with the assessment literature.[245] Depending on the climate scenario selected and climate model used, the increase in cumulative reactive adaptation costs relative to the reference period range from $27 to $62 billion by 2099 (discounted at 3%) (see Appendix A.9). The study suggests that the use of sensor technology combined with changes in operating policy could reduce delays by limiting temperature-based speed restrictions for specific locations. These proactive adaptations could reduce costs to $1.1 to $26 billion by 2099 (discounted at 3%), depending on the climate scenario and model used.

Although national-scale analysis of climate change impacts on rail has not been done in the U.S., a recent study suggests that costs of climate-change related delays are projected to increase significantly across Europe under RCP8.5.[246] The study projects that Southern Europe will experience the highest increased risk for rail track buckling.

The proactive adaptation evaluated in this study is not the only approach to reduce train delays caused by climate change. Continuing innovations in track management and potential changes in track materials may provide additional opportunities. In addition, since rail lines must be replaced every 50 to 60 years, there may be scheduled opportunities to use more resilient infrastructure. Rail lines that anticipate implementing new rail technologies, such as high-speed rail, or that focus on specific types of freight, may implement new technologies optimized for those options.

Although the focus of this study was on temperature effects, additional climate change considerations can affect the vulnerability of the rail system. Precipitation changes could result in flooding that affect bridge or railbed stability, and thus require additional investment to stabilize the infrastructure. Similarly, increased threats from wildfires and hurricanes could exacerbate potential vulnerabilities.

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[245] Schwartz, H.G., M. Meyer, C.J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

[246] Nemry, F. and H. Demirel, 2012: Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures. JRC Scientific and Policy Reports. European Commission. Available online at http://ftp.jrc.es/EURdoc/JRC72217.pdf