Appendix G. Roads

1. Introduction

Roads represent the primary mode of transportation in the U.S. and most Americans spend a significant amount of time traveling on roads every day. According to the latest National Household Travel Survey,[1] the average American takes 1,500 trips per year, and the average driver spends almost an hour a day behind the wheel. For various reasons, climate change is likely to increase the amount of time it takes to travel the same distance on roads. Weather already causes traffic delays regularly. Continuous hot days cause cracking and rutting of paved road surfaces, repeated heavy rainfall causes erosion and damage, flooding events can wash away roads and require repair, and abnormally high tides that flood low-lying roads can result in periodic road closures. With increased temperatures, more frequent heavy rainfall and flooding, and sea level rise, road conditions may worsen resulting in more traffic delays or expensive adaptations to the road network.

Socially vulnerable populations may experience more or less traffic delays in the future because of the geographic variations in climate across the contiguous U.S. and differences in road network characteristics in areas where they tend to travel. Since adaptation of the road network can alleviate these delays for road users, adaptation may also be more or less effective in areas where socially vulnerable populations are currently living. This appendix explores the relationship between changes in traffic delays and populations generally characterized as socially vulnerable.

[1] U.S. Department of Transportation, Federal Highway Administration. 2017. National Household Travel Survey. URL: http://nhts.ornl.gov.

The remainder of this appendix relies on this framework to uncover how socially vulnerable groups may be exposed to these risks relative to non-socially vulnerable populations. Section 2 provides an overview of the importance of transportation and mobility for socially vulnerable populations. Section 3 describes how climate change impacts transportation on roads. The methods for estimating the impact of climate change on traffic delays is described in Section 4, and Section 5 describes the approach for evaluating the impacts on socially vulnerable groups. Finally, Section 6 describes the results.

2. Social Vulnerability and Transportation

Transportation plays a vital role in highly mobile modern societies by creating links between people, opportunities, and resources, among others. Distance between people and places creates a kind of friction that requires resource expenditures, including time, that vary by many factors such as the availability of modes of transport (public or individual), the conditions of transport infrastructure (e.g., road surface conditions), health and safety (e.g., traffic accident likelihood or air quality impacts), and legal restrictions (e.g., loss of license).

An individual's potential mobility—access to places and opportunities—are often limited by that individual's time and financial resources, which vary across the U.S. based on factors such as wealth, gender, religion, and age.[2] Lower income individuals travel less than those with higher income both in person-miles traveled[3] and number of trips[4] (see Figure 2). Despite traveling less, commuting expenses as a portion of total income are higher for the working poor, compared to those with higher income (Figure 2). The working poor also tend to choose less expensive options for transport, which indicates that transportation costs create a level of economic burden for these individuals.[5] Time budgets also make transportation more burdensome for some than others. Also, time sensitivity varies disproportionally across genders, religious affiliations, and ages, where society or an individual's social networks create additional pressures, such as those related to a women's role in the household or religious obligations.[6] Income and education levels are also related to job security where lower income or education often means lower job security.[7] As a result, recurring late penalties caused by traffic delays may cause some workers to lose hourly compensation or be perceived as unreliable.

[2] Martens K. 2012. Justice in transport as justice in accessibility: applying Walzer's 'Spheres of Justice' to the transport sector. *Transportation* 39, 1035-1053(2012).

[3] Bureau of Transportation Statistics (BTS). 2016. Passenger Travel Facts and Figures 2016. U.S. Department of Transportation. Available < https://www.bts.dot.gov/sites/bts.dot.gov/files/docs/PTFF%202016_2l.pdf> Accessed April 15, 2020.

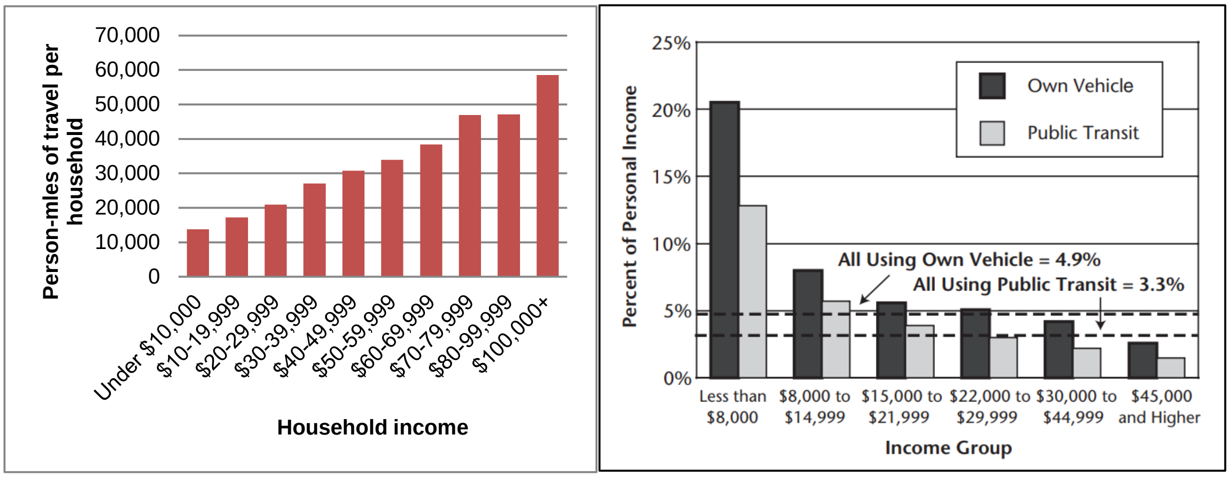
[4] Bureau of Transportation Statistics (BTS). 2017. Summary of Travel Trends: 2017 National Household Survey. U.S. Department of Transportation. Available < https://nhts.ornl.gov/assets/2017_nhts_summary_travel_trends.pdf> Accessed April 15, 2020.

[5] Bureau of Transportation Statistics (BTS). 2003. Commuting Expenses: Disparity for the Working Poor. U.S. Department of Transportation, Issue Brief Number 1. Available: https://www.bts.gov/sites/bts.dot.gov/files/legacy/publications/special_reports_and_issue_briefs/issue_briefs/number_01/pdf/entire.pdf> Accessed April 15, 2020.

[6] Kwan Mei-Po. 2000. Gender Differences in Space-Time Constraints. *Area* 32.2, 145-156.

[7] Lewchuk W, Laflèche M, Procyk S, Cook C, Dyson D, Goldring L, Lior K, Meisner A, Shields J, Tambureno A, and Viducis P. 2016. The Precarity Penalty: How Insecure Employment Disadvantages Workers and Their Families. *Alternative Routes: A Journal of Critical Social Research*, 27. ISSN 0702-8865 (Print), ISSN 1923-7081 (Online).

Figure 2. Relationship between Income and Person-Miles Traveled (left) and Relationship between Income and Commuting Expenses as a Portion of Income (right)



There are also important feedback loops where transportation mobility limitations may adversely affect other types of mobility, such as income, wealth, or education mobility. Transportation mobility limitations affect an individual's ability to seek opportunities such as employment, education, and access to lower prices, as well as cultural or recreational opportunities that may develop important social connections.[8,9] As a result, distance mobility restrictions keep individuals from moving out of higher vulnerability situations by limiting opportunities, which in turn sustains distance mobility restrictions.

In 2012, Hurricane Sandy caused significant damage in the New York City (NYC) area. Disruptions to transportation were widespread and prolonged. Kontou et al. (2017)[10] surveyed NYC area commuters via telephone to determine major drivers of changes in commuting patterns in the aftermath of Hurricane Sandy. The authors found that individuals with higher incomes were more likely to telecommute for longer after the storm. This study also found that women's commutes were not more significantly altered than men's, but did find that the presence of children in the household impacted commuting when day cares or schools were closed. Commuters that returned home during peak commuting hours were less likely to telecommute. The authors note that the association of traveling during peak commute hours and less telecommuting may be due to these commuters working less flexible jobs; individuals traveling during peak commute hours may not have the option to travel at other times or work from home.

Limited transportation connectivity has also been linked with increased social vulnerability. Parry et al.[11] assessed 310 urban centers in Brazil and found that urban centers with less connectivity have higher levels of social vulnerability because these centers are more sensitive to climatic shocks and have lower

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[8] Hess DB. 2005. Access to Employment for Adults in Poverty in the Buffalo-Niagara Region. *Urban Studies*, Vol. 42, No. 7, 1177-1200. DOI: 10.1080/00420980500121384

[9] Forkenbrock DJ, and Weisbrod GE. 2001. Guidebook for Assessing the Social and Economic Effects of Transportation Projects, NCHRP Report 456, Transportation Research Board, National Academy Press (www.trb.org).

[10] Kontoua E, Murray-Tuite P, and Wernstedt K. 2017. Duration of commute travel changes in the aftermath of Hurricane Sandy using accelerated failure time modeling. *Transportation Research*, Part A Policy and Practice, DOI: 10.1016/j.tra.2017.04.015

[11] Luke P, Davies G, Almeida O, Frausin G, de Moraés A, Rivero S, Filizola N, and Torres P. 2018. Social Vulnerability to Climatic Shocks Is Shaped by Urban Accessibility, *Annals of the American Association of Geographers*, 108(1):125-143, DOI: 10.1080/24694452.2017.1325726

adaptive capacities than more highly connected urban areas. The authors found that five social sensitivity indicators (demography, sanitation, ethnicity, health, and education) and four adaptive capacity deficit indicators (health care provision, education provision, urban population growth, poverty) were significantly higher in remote urban areas. In the Netherlands, Kirby et al.[12] conducted a social vulnerability analysis for the province of Zeeland, with a focus on flood hazards. Using a principal component analysis, they found that transportation access was a key metric of vulnerability. Specifically, distance from the nearest train station was the fifth-highest loading variable; the seven highest variables explain 66% of the variance in social vulnerability. The authors note that only about 60% of residents in Zeeland own a personal vehicle, so access to transportation via rail plays an important role in the lives of many residents.

Socially Vulnerable Populations

This section further explores the broad categories of social vulnerability used in the remainder of this appendix and how these populations may be exposed to traffic delays more acutely than individuals in the "reference population" – that is the population that is not in that specific socially vulnerable category. These groups listed below are populations for which increased traffic delays may be a larger burden for the same amount of increased delays. The reasoning behind this is described for each group below.

- ***Lower income:*** Low income workers are more likely to get paid on an hourly basis and work in jobs with fixed hours.[13] As a result, they may be more vulnerable to consequences of unexpected traffic delays.
- ***Black and African American, Asian, Native American, Pacific Islander, and Hispanic/Latino individuals (referred to subsequently as "Minority"):*** Increased travel times may reduce the accessibility of opportunities for employment or social engagement further from their home, exacerbating trends of reduced proximity of job opportunities to minority and low income populations.[14]
- ***No high school diploma:*** There is a lack of comprehensive research on the association between educational attainment and vulnerability to traffic delay-related impacts. However, to the extent that those with lower educational attainment have lower job security, road delays could further exacerbate this vulnerability.[15]***65 and older:*** Limited access to transportation among

[12] Kirby RH, Reams MA, Lam NSN, Zou L, Dekker GGJ, Fundter DQP. 2019. Assessing Social Vulnerability to Flood Hazards in the Dutch Province of Zeeland*, International Journal of Disaster Risk Science*, 8:1-11.

[13] Theiss, R. The future of work: Trends and challenges for low-wage workers. Economic Policy Institute Briefing Paper #341. https://files.epi.org/2012/bp341-future-of-work.pdf.

[14] Kneebone E, and Holmes N. 2015. The growing distance between people and jobs in metropolitan America. Brookings Institute Metropolitan Policy Program working paper. Washington, DC. Available at: https://www.brookings.edu/wp-content/uploads/2016/07/srvy_jobsproximity.pdf

[15] Lewchuk W, Laflèche M, Procyk S, Cook C, Dyson D, Goldring L, Lior K, Meisner A, Shields J, Tambureno A, and Viducis P. 2016. The Precarity Penalty: How Insecure Employment Disadvantages Workers and Their Families. *Alternative Routes: A Journal of Critical Social Research*, 27: 87-108.

older adults has been shown to cause missed or delayed medical care appointments, [16] and more, generally, to limit access to health

- care.[17] Traffic delays associated with climate change may further exacerbate this vulnerability..

Although this analysis does not consider current road conditions or budget strategies of road maintenance agencies, these factors may further leave disadvantaged communities at higher risk than the reference population. There is some evidence that historical spending on road maintenance may already favor more affluent communities. A study in Oakland, CA suggests lower-income communities receive less of the budget for road maintenance, where 20% of budget is set aside to address "complaints."[18] These complaints are likely to be from communities that have the time and budget, as well as connections, to make sure they are heard. Transportation agencies may also choose to "disinvest" in transportation infrastructure as a budget balancing strategy. Transportation assets are prioritized based on their importance or criticality, and resources are deliberately shifted away from lower priority to higher priority assets. However, without deliberate consideration of vulnerable communities, disinvestment plans may disproportionally impact socially vulnerable populations. A case study of roadway infrastructure in Vermont highlighted how consideration of socially vulnerable populations could significantly shift which network segments were targeted for disinvestment.[19]

3. Climate change and traffic delays

Traffic Delays from Precipitation and Temperature Impacts

Climate change can impact road surface conditions and structural integrity in various ways. As temperatures increase, binder material will age faster and rutting in asphalt surfaces will be more common. Areas of the country that are projected to have increases in precipitation are likely to see more cracking and erosion, which impact the structural stability of roads. More frequent and/or more severe flood events will cause more damage to roads, especially since the existing storm drainage infrastructure is generally designed based on historical flood records. In addition, changes in freeze-thaw cycles could cause additional road rutting. These impacts are likely to increase road maintenance costs compared to historical spending in order to deliver the same level of service in the future.[20] Due to constraints of governing bodies that maintain these roads, including budgets, there may be a decline in the level of service for roads that would have direct impact on the drivers. For example, road rutting is likely to both increase traffic by decreasing a comfortable driving speed and increase vehicle operating costs.[22]

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[16] Kara E. MacLeod, David R. Ragland, Thomas R. Prohaska, Matthew Lee Smith, Cheryl Irmiter, and William A. Satariano. Missed or Delayed Medical Care Appointments by Older Users of Nonemergency Medical Transportation, *Gerontologist*, 55(6), 1026–1037. doi:10.1093/geront/gnu002

[17] Syed ST, Gerber BS, and Sharp LK. 2013. Traveling towards disease: transportation barriers to health care access. *J Community Health,* 38(5):976-993. doi: 10.1007/s10900- 013-9681-1.

[18] Bradford, Ben (2019) One Way Oakland is fighting racial inequality? By Fixing Potholes. Marketplace. Available < https://www.marketplace.org/2019/05/15/one-way-oakland-is-fighting-racial-inequality-by-fixing-potholes/> Accessed April 15, 2020.

[19] Novak, D.C., J.F. Sullivan, K. Sentoff, J. Dowds. 2020. A framework to guide strategic disinvestment in roadway infrastructure considering social vulnerability. *Transportation Research Part A* 132: 436–451 https://doi.org/10.1016/j.tra.2019.11.021

[20] Chinowsky P, Price J, Neumann J (2013) Assessment of climate change adaptation costs for the U.S. road network. *Glob Environ Chang* 23(4):764–773, http://www.sciencedirect.com/science/article/pii/S0959378013000514

Chinowsky et al.[21] develops an approach for estimating climate-related changes in road maintenance and construction costs such that the current level of service provided by both paved and unpaved roads is maintained over time. This approach and cost estimates were most recently updated in Neumann et al. (2021) to include a No Adaptation case where decision-makers limit their annual spending on repairs to what they have spent historically (average of the base period, 1986-2005). In the cases where roads are not maintained beyond historical spending, direct costs from additional vehicle operating costs and indirect costs caused by travel delays from worsened road conditions accumulate over time. Neumann et al.[22] estimates that, in addition to historical spending, annual costs will increase by $90 and $140 billion by 2050 and by $150 and $340 by 2090 for RCP 4.5 and RCP 8.5, respectively, for the No Adaptation case. These annual costs are reduced significantly with adaptation to increasing by $7.8 and $8.4 billion by 2050 and by $3.7 and $4.8 by 2090 for RCP 4.5 and RCP 8.5. Under this Proactive adaptation scenario, maintenance budgets and investments are made with a forward-looking consideration of climate changes in the future decades.

These costs will impact communities across the U.S. differently due to factors such as transportation department budgets, how budgets are distributed geographically, and how these agencies adapt to changing conditions.

Road Closures from High Tide Flooding Events

High tide flooding (HTF), which is 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 have historically 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. High tide flooding events impact low-lying infrastructure such as roads and traffic, as well as underground stormwater systems, sewer systems, and wires.[23] 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.[24] One of the largest impacts of HTF events is traffic delays caused by floods across road networks, causing additional congestion and longer travel times.[25]

Jacobs et al.[25] found that delays would increase substantially along the East Coast, reaching 1.2 billion vehicle-hours by 2060 and 3.4 billion by 2100, whereas delays currently are roughly 100 million vehicle-

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[21] Chinowsky P, Price J, Neumann J (2013) Assessment of climate change adaptation costs for the U.S. road network. *Glob Environ Chang* 23(4):764–773, http://www.sciencedirect.com/science/article/pii/S0959378013000514

[22] Neumann JE, Chinowsky P, Helman J, Black M, Fant C, Strzepek K, and Martinich J. 2021. Updated estimates of physical and economic risks from climate change to US infrastructure: risks of inaction and the economics of adaptation for roads, rail, and coastal development, *Climatic Change* doi:10.1007/s10584-021-03179-w

[23] Sweet W, Dusek G, Obeysekera J, Marra JJ. 2018. Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS 086

[24] Moftakhari H, AghaKouchak A, Sanders BF, Matthew RA, & Mazdiyasni O. 2017. Translating uncertain sea level projections into infrastructure impacts using a Bayesian framework: Impact assessment of SLR projections. *Geophysical Research Letters*, 44, 11,914–11,921. https://doi.org/10.1002/2017GL076116

[25] Jacobs JM, Cattaneo LR, Sweet W, & Mansfield T. 2018. Recent and future outlooks for nuisance flooding impacts on roadways on the US East Coast. *Transportation Research Record: The Journal of the Transportation Research Board*. https://doi.org/10.1177/0361198118756366

hours. Fant et al.[26] extends Jacobs et al.[25] to include the Gulf and West Coasts and provides 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. The study finds that without direct adaptation to roads, annual costs across the U.S. are $1.3 and $1.5 billion in 2020 for RCP 4.5 and RCP 8.5, respectively. These annual costs increase to $28 and $37 billion in 2050 and $220 and $260 billion in 2100 for RCP 4.5 and RCP 8.5, respectively. These costs to individual drivers are disproportionately distributed geographically. For example, the Gulf bears about two thirds of the total costs across the century.

4. Methods

The approach in this study uses results from Neumann et al.[22] for precipitation and temperature-driven impacts to roads and the subsequent effects on traffic, and Fant et al.[26] for coastal HTF impacts to traffic. Since precipitation and temperature impacts are driven by changes in atmospheric climate variables and high tide flooding is driven by sea level rise, these two climatic drivers are kept separate for much of this appendix. While those in the coastal community may encounter traffic delays increasing from both types of hazard drivers, combining atmospheric changes modeled with GCMs and sea level rise projections is challenging, with little consensus in the literature on the best approaches for doing so.

Both approaches develop traffic delay risks with and without adaptation. The adaptation scenarios are not meant to be a prediction of how decision-makers will respond to changes in adverse climatic conditions. Instead, these scenarios provide a range of planning alternatives reflecting whether future climate changes are considered in the design and maintenance of infrastructure. In reality, strategies for adaptation and infrastructure technology will likely vary across the U.S. and over time.

Processing of Climate Data

Climate data were downscaled from the native GCM spatial resolution to a 1/16 latitude/longitude degree resolution covering the contiguous U.S. The dataset provides daily projections for global integer degree arrival times for three variables: daily maximum temperature (t_{max}), daily minimum temperature (t_{min}), and daily precipitation. Scenarios of sea level rise SLR are based on data described in Appendix C.

Changes in Traffic Delays from Temperature and Precipitation Damage to Roads

Roads can be damaged from temperature and precipitation through a variety of mechanisms that also depend on the road material or road type. For example, gravel and unpaved roads are more susceptible to washout from high-intensity storms, but paved roads are more susceptible to buckling from increased temperatures. The analysis of road damage from exposure to weather includes many of the major mechanisms that cause road damage and also provides a scenario where a forward-looking adaptation strategy is able to maintain the same historical levels of service of the road. The Infrastructure Planning

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[26] Fant C, Jacobs JM, Chinowsky P, Sweet W, Weiss N, Sias JE, Martinich J, and Neumann JE. Mere nuisance or growing threat? 2021. The physical and economic impact of high tide flooding on US road networks. *Journal of Infrastructure Systems* doi: 10.1061/(ASCE)IS.1943-555X.0000652

Support System (IPSS) model was used to connect incidence of each climate stressor to damage to roads and the need for repair.[27]

In the No Adaptation scenario, road repairs are assumed to be made within the current transportation maintenance budget. Any additional costs beyond the current budget will result in road damage. Historic climate data (1986-2005) is used to value the damage associated with the present-day conditions. These historic costs are assumed to be the future budget constraints for the No Adaptation scenario only.

To estimate vehicle delays associated with lack of repair, first the change in the international roughness index (IRI) of roadways resulting from changes in temperature is calculated. Research by Qiao et al. (2013) found that a 5% increase in temperature results in an average rut depth of 1.2-2 inches over a 40 year time period.[28] Using this relationship, a generalized correlation between temperature increase and rutting was developed, which assumes that rut depth increases gradually and linearly over the life span of the road, and that in a year in which the average temperature increases by 5% there will be an additional 0.04 inches of rutting. To estimate delays, a relationship between present serviceability rating (PSR) and free-flow speed developed by Wang et al. (2013), combined with research by Al-Omari and Darter (1994), converts IRI to PSR.[29] Delays are estimated at the 1/16 degree grid cell level.

The road inventory used in this analysis includes the miles of road for three types of road surface material, which are paved, gravel, and unpaved. The atmospheric hazards include increases in hot days, high-intensity extreme flooding events, and continued heavy precipitation. The analysis includes two types of impacts from precipitation because while flood damage is more visual and immediate, repeated heavy precipitation can also damage roads. The specific effects of these climate hazards vary by road surface material. The list below describes the impacts and how damages and impacts are determined.

Paved Roads: The majority of road traffic in the U.S. travels on paved roads, which are expensive to build, but have a longer expected service life and are less susceptible to washout. The specific impacts with and without adaptation are described in Table 1 below.

[27] See https://resilient-analytics.com/ipss for details, also Neumann et al. (2021)

[28] Qiao Y, Flintsch G, Dawson A, Parry T. 2013. Examining Effects of Climatic Factors on Flexible Pavement Performance and Service Life. *Transportation Research Record: Journal of the Transportation Research Board*. 2349. 100-107. 10.3141/2349-12.

[29] Wang T, Harvey J., Lea JD, Kim C. 2013. Impact of Pavement Roughness on Vehicle Free-Flow Speed. *UC Davis: University of California Pavement Research Center*; and Al-Omari B., Darter, MI. Relationships Between International Roughness Index and Present Serviceability Rating, *Transportation Research Record* No. 1435, 1994.

Table 1. Impact Modeling of Temperature and Precipitation Effects on Paved Roads

CLIMATE DRIVER	DESCRIPTION OF EFFECT	NO ADAPTATION SCENARIO	PROACTIVE ADAPTATION SCENARIO
Temperature	Increased temperatures cause softening of asphalt which results in increased cracking as well as rutting over time.	Thresholds are based on binder design guidelines which are compared against design conditions and future temperature increases with damage being determined by pavement studies. Without adaptation, the cracking and rutting of the roads in the locations where increased temperatures occur are repaired through patching as per the standard processes. The same binder mix is used at the time of road rehabilitation.	Cost-effective adaptation adjusts the mix of asphalt to better accommodate changes in temperature. Local practices may also include increasing the cycle of resealing to reduce damages
Flooding	Culvert and road washout occur based on changes in flood return intervals. Localized damage occurs based on the severity of the flood.	Without adaptation, a flood occurrence will cause a level of damage to a section of road based on the damage curves used in the Neumann et al. work. Repairs to the road, including top layer repaving, base layer replacement, and culvert replacement, can be conducted in that year up to the amount that is allocated in the budget. No change in design is considered based on past or future climate change. The same capacity culvert is installed at the time of road rehabilitation	At the time of repair, or at the time of regular maintenance and rehabilitation activities, the magnitude of future flooding is anticipated and replacement culvert capacity is optimized to reflect those conditions.
Repeated heavy precipitation	Erosion, base layer damage from water infiltrating through cracks in the roadway, requires additional maintenance to ensure the same level of service. The level of damage depends on the age of the road and the number of heavy rainfall events that exceed damage threshold levels.	Without adaptation, damages are repaired through patching of the surface and filling of the base where required. No change in design is considered based on past or future climate change and no change in base design is used at rehabilitation.	With adaptation, design changes are considered - increases in heavy precipitation require a change in the road base as well as possible changes to the surface depending on the amount of precipitation. Base layer strengthening including increasing the base depth is the first adaptation. In severe cases where several damage thresholds are exceeded, a widening of the shoulder is required to allow drainage from the road surface.

Gravel Roads: Gravel roads are more susceptible to flooding or repeated heavy precipitation but are not susceptible to damages from temperature. Flooding causes the top layer of the gravel road to be disturbed requiring a relaying of the gravel surface. For both flooding and repeated heavy precipitation, erosion of the base layer can require filling areas where erosion has occurred. Generally, culverts are not installed, so damage is restricted to resurfacing the road. In large flood events, a regrading of the road is necessary. Without adaptation, the road is regraded when necessary and the relaying of the gravel surface is completed consistent with standard procedures. Repair of the base layer is completed by filling where required. No change in surface or base design is used at rehabilitation. With adaptation, two options could be used at the time of rehabilitation of replacement: 1) the thickness of the top layer can be increased to better withstand smaller (less than 50 year) floods; and 2) the road can be upgraded to a paved road to withstand the larger floods and enhance resiliency.

Unpaved Roads: Similar to gravel roads, unpaved roads are not damaged by high temperatures but are vulnerable to precipitation and flooding. Flooding causes the unpaved road to be washed out requiring a regrading of the road and a replacement of the top layer. Precipitation causes erosion and depends on the level of precipitation increase, the slope of the road and the amount of traffic on the road. Without adaptation, localized damage to unpaved roads is typically repaired through filling and patching and does not require heavy machinery. Persistent heavy precipitation that causes erosion over time requires regrading of the road. No changes in the design are implemented in response to changes in damage. With adaptation, when unpaved roads are subject to repeated damage, the road is upgraded to a gravel or paved road.

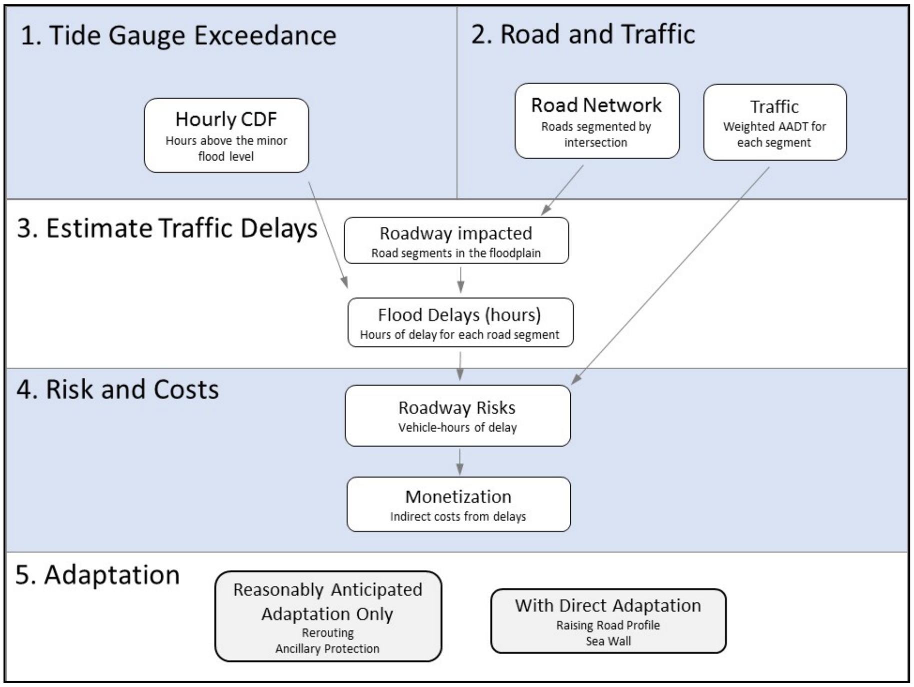
Traffic delays: Traffic delays in the road impact model are the result of construction activity required to repair damages to the historical level of service. Without adaptation, maintenance budgets can be exhausted, and some roads are left unrepaired, which causes additional traffic delays. Any additional costs beyond the current budget could also result in road damage. Road damage that is not repaired causes a decrease in the free flow speed along a road, which increases traffic delays. Some vehicles can avoid damaged roads or roads undergoing repair work – to estimate the degree to which re-routing is possible a “route redundancy” index is and applied to reduce delays when there are options for alternate routes.

Changes in Traffic Delays from High Tide Flooding Events

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.

The approach to estimating impacts is described in more detail in Fant et al.,[26] and is outlined in Figure 3. In the first step, the hourly distribution of tide gauge water levels (a cumulative density function, or CDF) is determined (#1 in the figure). The road network is segmented by intersections or ramps and traffic data are assigned to each segment (#2 in figure). These datasets are used with a mapping of the floodplain to identify vulnerable roads and flood duration (#3). Roadway risk, measured in vehicle hours of delay, is calculated as the product of flood duration and traffic. The risk is then monetized using hourly rates for passenger and freight truck traffic delays (#4). Two types of adaptation are simulated (#5): reasonably anticipated adaptation, which includes driver-initiated rerouting and ancillary protection from actions to protect property; and direct adaptation, where, in addition to reasonably anticipated adaptation, actions are taken to alleviate delays by raising the road profile above flood height, or building hard structures such as sea walls or bulkheads. For “direct adaptation,” the model places hard structures in locations needed to directly respond to the risk of HTF, and only for the road sections that are vulnerable. Both capital and maintenance costs for hard structures are higher for open ocean locations, relative to back-bay locations, to account for the higher wave height and energy encountered in open ocean locations. Details are provided in Fant et al. [26]

Figure 3. Framework for Estimating Traffic Delay from High Tide Flooding Events



The method adopts recently developed "minor" flood levels[23] developed by NOAA as thresholds for HTF events. Using 19-years of hourly water levels spanning from 1999 to 2017, flooded hours are estimated using the approach described in Jacobs et al.[25] First, the hourly record of water levels is detrended and brought to the common sea level rise baseline year, 2000. Using an empirical CDF, hours above the HTF threshold level provides the number of hours flooded for the baseline. These flooded hours are then estimated over time by adding the differences from the sea level in 2000 to the six local sea level rise projections from Sweet et al.[30] to the water level CDF. This approach is limited to tide gauge measurements and does not consider situations where flooding is intensified or induced by precipitation. NOAA's flood maps, derived from 30-cm resolution LIDAR digital elevation data using a modified bathtub approach, are used to delineate the flood extent at the specified levels.[31] Road segments within the NOAA flood extent are designated as road segments vulnerable to HTF. Using the NOAA flood map extents limits the analysis to the roads that are currently vulnerable to HTF. With rising sea levels, flood extents are expected to increase and additional roads could become vulnerable.

[30] Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, and Zervas C. 2017. Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services.

[31] Available through NOAA's sea level rise viewer, https://coast.noaa.gov/slr/

A non-trivial step of the process involves developing road segments, divided at intersections using road network data provided by state DOTs. The number of segments flooded at intersections is the basis for understanding how traffic delays are estimated, as intersections provide on- and off-points for vehicles and allow for more accurate use of traffic data. The number of vehicles that would travel on these flooded segments, but find an alternative route due to flooding, are summed for the hours the road is inundated from HTF events depending on how often the road is flooded and for how long.

Reasonably Anticipated Adaptation: This base traffic delay risk is reduced by factors that should occur independent of decisions made by road maintainers, processes termed "Reasonably anticipated adaptation." The method considers two reasonably anticipated adaptations to reduce traffic delay risk, (1) driver-initiated or official detour rerouting that directs drivers around the inundated road and (2) ancillary protection, where high tide flooding is prevented using protective strategies, such as sea walls and beach nourishment that are built to protect nearby land and structures, but also prevent flooding on roadways. These adaptations, which are each discussed in the following paragraphs, form the basis of the traffic delay risk metric described in the next section, which is the traffic delay expected without direct adaptation.

Alternative routes take advantage of route redundancy in the road network, the effectiveness of which varies by location. In this study, route redundancy uses a slightly modified version of the Traffic Intensity indicator to reduce delays where the road network is extensive and more likely to provide reasonable alternative routes. The details of this approach are described in Fant et al.[26]

In addition to road redundancy, the method also considers avoided flooding and delays that result from actions that are taken to protect coastal property. The National Coastal Properties Model (NCPM) estimates damage from storm surge and inundation losses and compares these to various adaptation options including sea walls and beach nourishment, indicating the areas protected behind these improvements. Because these adaptation strategies are designed to protect against storm surge water levels around the 100-year event, it is reasonable to expect they will also prevent roadway flooding during HTF events.

Direct Adaptation: The direct adaptation scenario considers the alleviation of HTF induced traffic delays through the implementation of adaptation strategies. While there are many conceivable ways to adapt to HTF, the model adopts two well established options: (1) build a sea wall to hold back the flood water and (2) raise the road profile above the effective threshold.

For each road, the simulated decision to adapt using one of these two options depends on the ratio of benefits to costs. Lorie et al. (2020),[34] among others, points out that in many cases the benefits need to be significantly higher than the costs to trigger action. This work adopts a benefit cost ratio of 4 as a requirement to trigger direct adaptation. The benefits of adaptation are the avoided traffic delay costs and the cost of adaptation is the construction material and labor costs to raise the elevation of the road or build a sea wall to hold back the flood. While the adaptation costs include estimates of material, labor, and construction delays, actual costs will include additional factors not included in the estimates reported in this chapter. For example, omitted costs include those associated with management, design, easements, and land acquisition. In addition, this framework implies that protection will be built without design or construction errors or schedule and permitting delays due to sociopolitical or budgetary issues. It is important to note that while construction of either of these protection types would divert flood waters away from the road, flooding may occur elsewhere as a result and additional costs would be incurred that are not captured in this analysis. Furthermore, these protections may have environmental impacts, such as preventing wetland migration.

For HTF impacts, traffic delays with adaptation reflect a combination of residual traffic delays on roads that do not qualify for protection as well as the construction delays from the direct adaptation implementation.

5. Methods for Assessing Social Vulnerability Dimensions

This analysis investigates if socially vulnerable populations are disproportionately more likely to be exposed to the risks associated with changes in traffic delays. Specifically, traffic delays are estimated instead of changes in maintenance costs because it is unclear who will absorb maintenance costs and how that burden might be distributed among individuals. Whereas, traffic delays are incurred directly by the road user, therefore providing a more reliable metric to evaluate disproportionality.

To understand the degree to which individuals are impacted by these changes in traffic delays with and without adaptation, this analysis develops targeted hazard metrics and estimates these at the census tract level. The models described in the previous section are used to develop two hazard risk metrics, both of which are applied in the traffic delay analyses resulting from temperature and precipitation and HTF events . These two metrics are described below.

- **Traffic delay risk:** This represents delays road users may face unless action is taken by decision-makers to directly address increases in delays through adaptation investments. For the temperature and precipitation impacts on roads, traffic delays result from construction, as well as increased surface roughness, that cannot be repaired without additional road maintenance budget compared to historical spending. For HTF, these are the traffic delays from reasonably anticipated adaptation, but without any investment in raising road elevations at low points or building sea walls. These traffic delays are distilled into the burden on the individual by first converting the delays into person-hours using the average number of people per vehicle and then by dividing the traffic delays by population. The result is the average number of hours of additional delay per person per year.
- **Exclusion from adaptation:** The purpose of this metric is to understand the relative reduction in delay if cost-effective adaptation is deployed across the road network, which includes actions targeted directly toward reducing traffic delay risk. The method calculates this metric by dividing the traffic delays remaining with cost-effective adaptation strategies by the traffic delay risk (traffic delays without adaptation). This essentially provides the proportion of delays remaining after adaptation. The higher the value, the less that area benefits from adaptation.

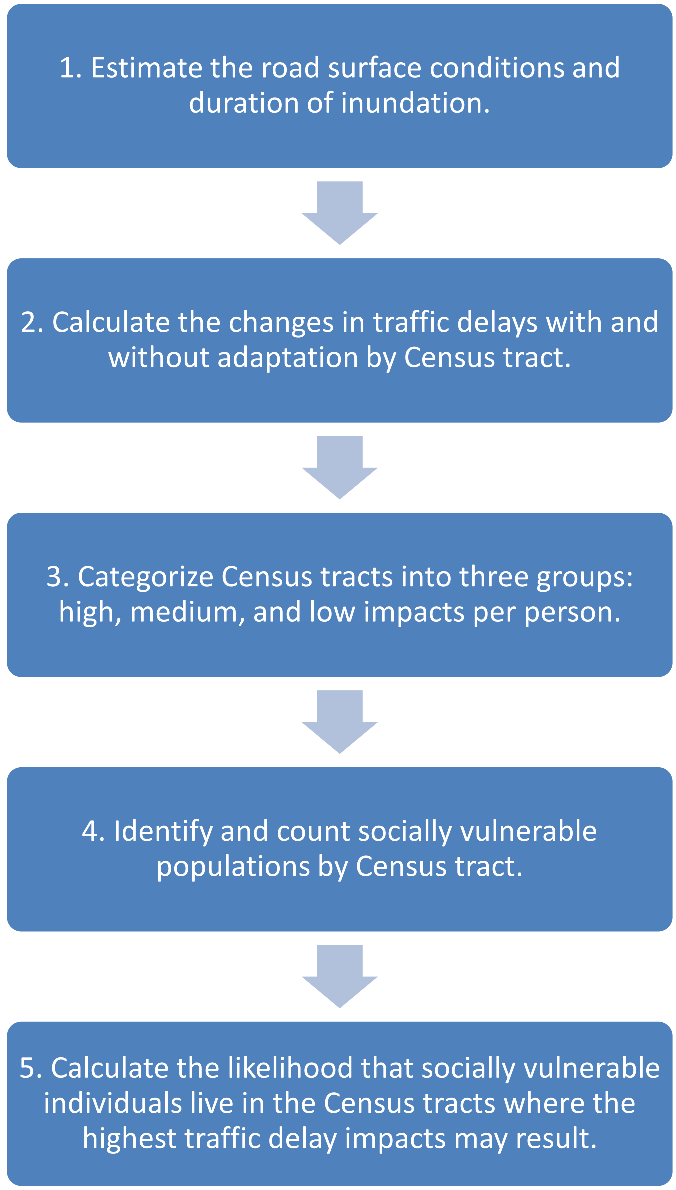
This analysis takes the Census tract as the unit of analysis. Although road users may travel outside their census tract regularly, these traffic delays most likely to have the highest impact on the individuals who live nearby.

To explore the traffic delay impacts on socially vulnerable populations, the method consists of five steps outlined in Figure 4 and described in further detail below.

Step 1: Estimate the road surface conditions and duration of inundation. Conditions are estimated for each road using the modeling approach described in Section 4 both with and without adaptation. Climate model projections of temperature and precipitation, as well as HTF flooding with sea level rise are used as inputs for each analysis. For more on the climate projection methods, see Appendix C.

Step 2: Calculate the changes in traffic delays with and without adaptation by Census tract. Traffic delays are estimated for the baseline period and future projections using the modeling framework discussed in Section 4. Without adaptation, increases in road roughness cause vehicles to slow down, and increasing the amount of time road users spend on the road for the same travel distance. Also, tidal flooding leaves roads unusable with water levels too high for most vehicles to traverse. These increases in time spent on the road are estimated and averaged at global mean temperature change degrees (1 through 5°C) and global mean sea level depths relative to the baseline at 25 cm increments up to 150 cm for HTF impacts. Establishing links between socioeconomic and demographic datasets, which are based on surveys sent to home addresses, and travel-related impacts, which may be far from home, generates uncertainty that cannot be fully resolved without additional information. To improve the match, this method focuses on arterials, collectors, and local roads (Functional Classes 3-7), and excludes interstates, freeways, and expressways (Functional Classes 1 and 2).

Figure 4. Five steps for Analyzing Impacts on Socially Vulnerable Road Users



Step 3: Categorize Census tracts into three groups: high, medium, and low impacts per person. The output from Step 2 is used to categorize Census tracts into three evenly sized groups. The high impact group comprises Census tracts with the most traffic delay risk or exclusion from adaptation to reduce delays, while the low impact group includes geographies with the least risk of traffic delays or adaptation exclusion. The focus of the analysis is on the composition of populations found in the high impact group.

Step 4: Identify and count socially vulnerable populations by Census tract. The method relies on data from the American Community Survey (2014-2018) at the Census tract level to count the number of individuals in socially vulnerable groups relative to the reference population. In the absence of projections describing how detailed demographics will shift over the century, this analysis assumes the relative distribution of socially vulnerable to the reference populations is fixed at 2014-2018, 5-year average. The four determinants of social vulnerability included in this analysis are: low income, minority, no high school diploma, and individuals 65 and older.

Step 5: Calculate the likelihood that socially vulnerable individuals currently live in the Census tracts that are where the highest traffic delay impacts from climate-driven changes in HTF may result. These likelihoods are expressed relative to the reference population and are calculated at the national and regional level. The likelihood measures are separately calculated for each social vulnerability metric. These likelihood metrics can be interpreted as the degree to which climate-induced traffic delays disproportionately affect socially vulnerable groups relative to the reference population.

6. Results

This section describes both the intermediate and final results of the analysis methods outlined in Sections 4 and 5. The traffic delays from temperature and precipitation damage to roads are discussed separately from the traffic delays caused by HTF events because they have different climate drivers. For temperature and precipitation, results by degree of global mean temperature change from the baseline are shown, while HTF traffic delays are shown in increments of 25 cm of global mean sea level rise.

Traffic Delays from Temperature and Precipitation Damage on Roads

Figure 5 and Figure 6 show the traffic delay risk per person at 2°C and 4°C, respectively, at the census tract level. Note that there are places where climate change results in reduced delays, which are included in the “Less than 0” category in light blue. At 2°C of global temperature rise from baseline, the average American would spend an additional 7 hours in traffic per year, and at 4°C, an estimated 23 hours per year without additional spending on road repair and/or adaptation. But these changes in traffic delay risk vary spatially from a small reduction in delay at the low end, to over 100 additional hours of delay per person per year. Since the average American driver spends about 350 hours traveling in a year,[32] 100 hours of additional travel time in the car would increase travel time by about 29%. The effects are not uniform across the U.S. Traffic delay risk tends to be lower for the coastal areas in the Southeast and Northeast, as well as eastern Texas. Much of Florida shows a decrease in traffic delay risk at 2°C, as does much of the Northern Plains and the Southwest, owing to changes in precipitation patterns that reduce risks to roads.

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[32] See U.S. Department of Transportation, Volpe Center, “How Much Time Do Americans Spend Behind the Wheel?” session in the *The Ongoing Transformation of the Global Transportation System* speaker series, delivered Monday, December 11, 2017, accessed from https://www.volpe.dot.gov/news/how-much-time-do-americans-spend-behind-wheel on April 1, 2021.

Figure 5. Projected Traffic Delay Risk from Temperature and Precipitation Damage on Roads at 2°C

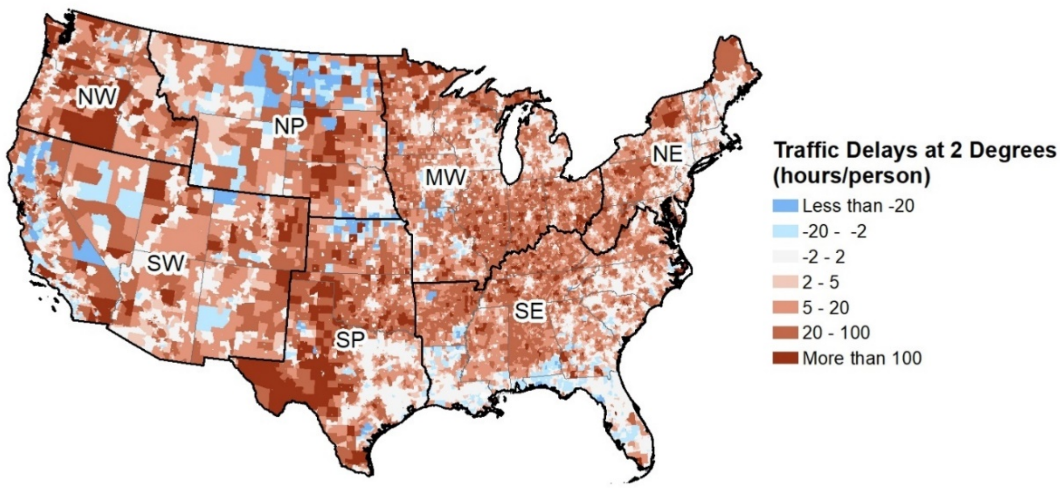
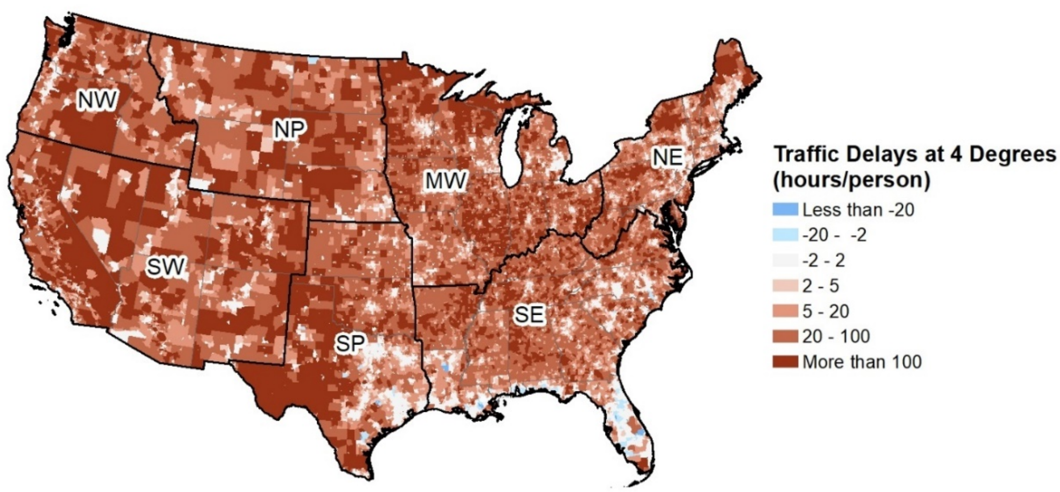
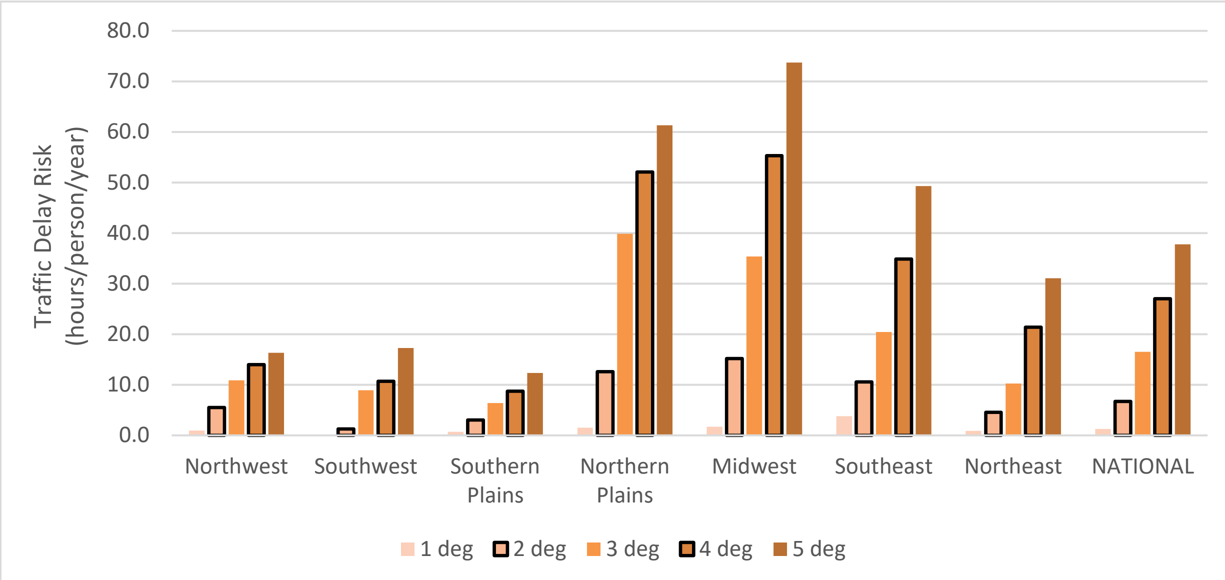


Figure 6. Projected Traffic Delay Risk from Temperature and Precipitation Damage on Roads at 4°C



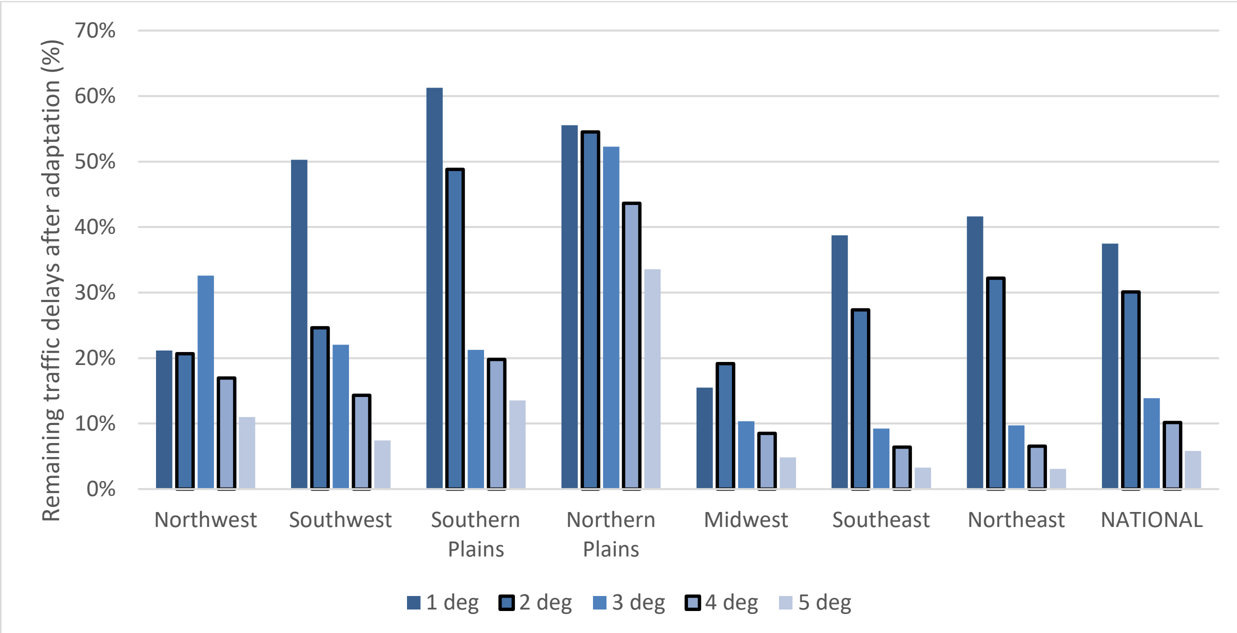
Since the analysis focuses on the areas with the worst climate-driven outcomes (the upper third of delay risk), Figure 7 shows the median traffic delay risk for each of the 5°C by region for the third of census tracts with the worst traffic delay risks for that geographic area. In other words, half the population in these high impact census tracts would have increased delays higher than the median values shown. For the NCA4 region-specific analyses of this chapter, the high impact tracts are determined relative to only the tracts in that region, as discussed in Section 5. In the Northwest and Southwest, as well as the Southern Plains, traffic delays are lower than the other four neighboring regions. The Midwest and Northern Plains have the highest median climate-driven traffic delay risk, both reaching over 50 hours per person by 4°C of warming.

Figure 7. Projected Median Traffic Delay Risk Per Person for the Upper Third of Census Tracts



Although the extent to which budgets for road maintenance might be increased to accommodate these climate change impacts is not known, the model projects that adapting roads to reduce delays is extremely cost-effective. The proactive adaptation scenario includes measures to account for future climate changes, therefore eliminating traffic delays from road roughness and repeated road repair with historical techniques that do not account for climate changes. The remaining are effects are traffic delays from any additional construction and routine maintenance time. As such, delays are reduced significantly with proactive adaptation, from an estimated 7 hours per person per year to 0.95 hours under 2°C, and from 23 hours to 0.72 hours at 4°C of warming. The lower delays at 4°C than 2°C is a result of the additional construction earlier in the simulation – benefits accrue later in the simulation, at 4°C, when additional benefits in delay reduction from those earlier projects are realized. While adaptation is effective in reducing delays, it is also not uniformly distributed across the U.S., which is why the "adaptation exclusion" metric is useful. Figure 8 shows the median exclusion from adaptation metric for each of the 5°C by region for the third of census tracts with the worst outcome. At higher degrees of warming, adaptation is more effective for the same reasons discussed - users benefit from earlier proactive road maintenance techniques. At 2°C, the Southern Plains and Northern Plains are projected to have the highest levels of remaining delays while the Midwest and Northwest regions both have the lowest remaining delays in the upper tercile or worst outcomes. Since the Midwest and Northern Plains have the highest levels of traffic delay risk (in Figure 7), this indicates that adaptation is more effective in the Midwest than the Northern Plains for both 2°C and 4°C. Also, for the Midwest, Southeast, Northeast, and Southern Plains, adaptation is projected to be at least twice as effective at 4°C than 2°C. For the Northern Plains and Southwest, adaptation effectiveness for these tracts does increase (by reducing remaining delays), but not as much as the other regions.

Figure 8. Projected Median Adaptation Effectiveness for the One Third of Census Tracts where Residual Delays After Adaptation are Largest



Traffic Delays from High Tide Flooding

The results for traffic delays from HTF are presented for the six coastal regions in Figure 9, showing total traffic delay risk for the coastal regions of the U.S. Projected traffic delay risk is highest in the Gulf regions, reaching about 200 hours per person per year at GMSL rise of 75 cm for the Southern Plains, and around 125 cm for Southeast-Gulf. Projected delays are lowest along the Pacific Coast, barely reaching 50 hours per person per year at 150 cm. As indicated in Appendix C, relative sea level rise (the combination of land and sea level changes) in the Pacific is projected to be lower than for the Gulf and Atlantic coasts for the same change in global mean sea level.

Figure 9. Projected Traffic Delays (hours per person per year) from High Tide Flooding In Coastal Areas

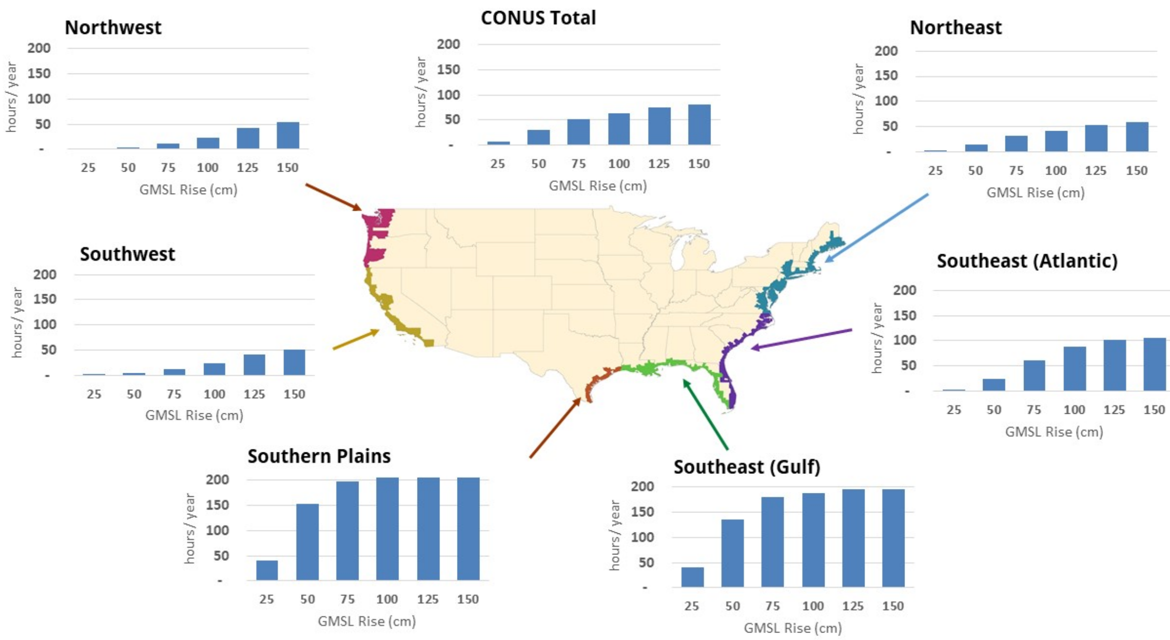
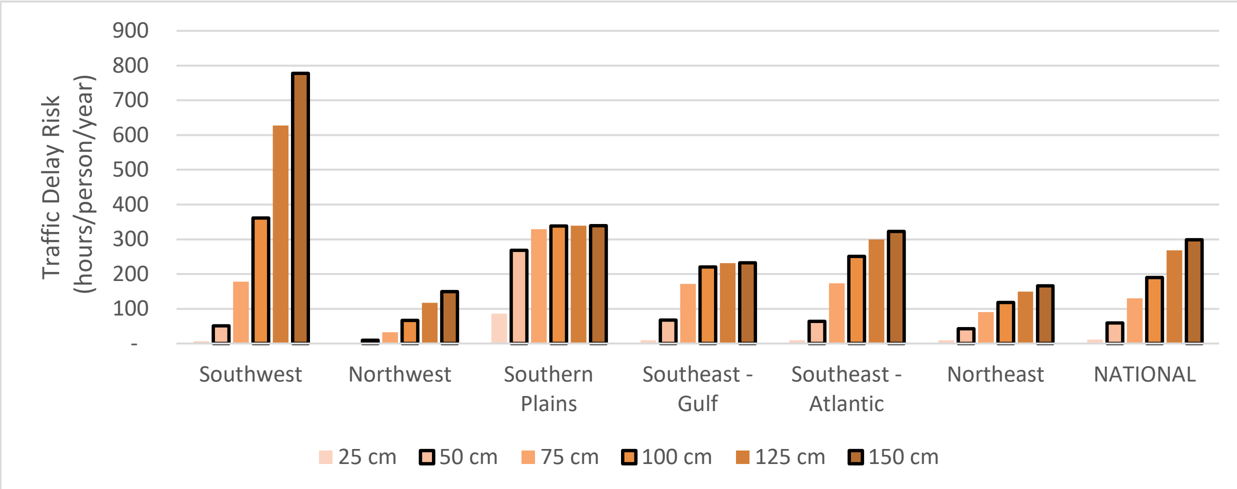


Figure 10 shows the median traffic delay risk for each of the 6 GMSL rise scenarios by region for the third of census tracts with the worst traffic delay risks for that geographic area. Differences between the coastal regions are significant. At 50 cm, projected traffic delays are highest in the Southern Plains (Texas), reaching almost 300 hours per year, and they are lowest in the Northwest at only 10 hours per year. At higher levels of rise, projected delays in the Southern Plains and Southeast Gulf start to flatten off because the diurnal tidal range in the Gulf is smaller than the other two coasts (Atlantic and Pacific). Even though projected traffic delays are relatively low in the Southwest, on average, the traffic delays are highly skewed such that the tracts with the worst outcomes in the Southwest can have higher median traffic delays than other regions, especially at levels above 100 cm. Note that in Figure 8 and subsequent results presentations for HTF, the Southeast NCA region is divided into a Gulf and Atlantic component, because of the substantial differences in local relative sea level rise and tidal ranges for the Gulf and Atlantic coasts (with land subsidence being higher in the Gulf area).

Figure 10. Projected Median Traffic Delay Risk from HTF for the Census Tracts with the Worst Outcome (upper tercile)



The adaptation scenario is projected to significantly reduces delays from high tide flooding. With direct adaptation, simulated delays are reduced from 31 hours per year to about 3 minutes per year for 50 cm and from 63 hours per year to about 7 minutes per year at 100 cm. There are many reasons why the simulated direct adaptation is particularly effective in reducing delays for HTF. First, delay risk escalates quickly as sea levels rise for the impacted roads. Once these roads reach the MHHW level, they are often flooded, on average, about half the days in a year. While raising these roads or building a sea wall is expensive, it reduces many of the hours of delay that are projected to occur under the no adaptation scenario. The second reason adaptation is so effective is that, using a cost-benefit test, roads with higher levels of traffic are fixed early in the simulation, thereby reducing delays significantly for each heavy-trafficked road. Many of the roads that do not pass the cost-benefit test are local roads with lower levels of traffic.

Risks to Socially Vulnerable Populations

Figure 11 presents the likelihood that individuals in the socially vulnerable groups analyzed currently live in areas with the highest projected traffic delays from HTF, relative to individuals in their reference groups. Those ages 65 and older are estimated to be more likely than younger individuals to live in high-impact areas, while individuals in the other three socially vulnerable groups are projected to be less likely than their reference populations to live in high-impact areas. Importantly, the projected decreases in relative risk for those three socially vulnerable determinants does not indicate that those populations are not vulnerable to traffic delays from temperature and precipitation, rather that they have a lower risk compared to their reference populations of living in areas with the highest impacts. Minority populations are projected to be much less likely to encounter the worst traffic delays, ranging from -40% to -48%. The main reason is that the higher impacts of traffic delays from temperature and precipitation damage are in areas with lower numbers of minority populations. For example, the Northern Plains have the lowest minority populations of the seven regions, but generally have the highest traffic delays per person.

Figure 12 shows the results for specific racial and ethnic groups. Individuals who identify as American Indian and Alaska Native are more likely to live in high-impact areas compared to their reference populations, as are White, non-Hispanic individuals. Since the areas most at risk of increased traffic delays without adaptation are in areas with higher White, non-Hispanic populations, this finding is to be expected.

Figure 11. Likelihood that Those in Socially Vulnerable Groups Live in Areas with the Highest Projected Traffic Delays from Climate-Driven Changes in Temperature and Precipitation, Relative to their Reference Populations (warming in °C)

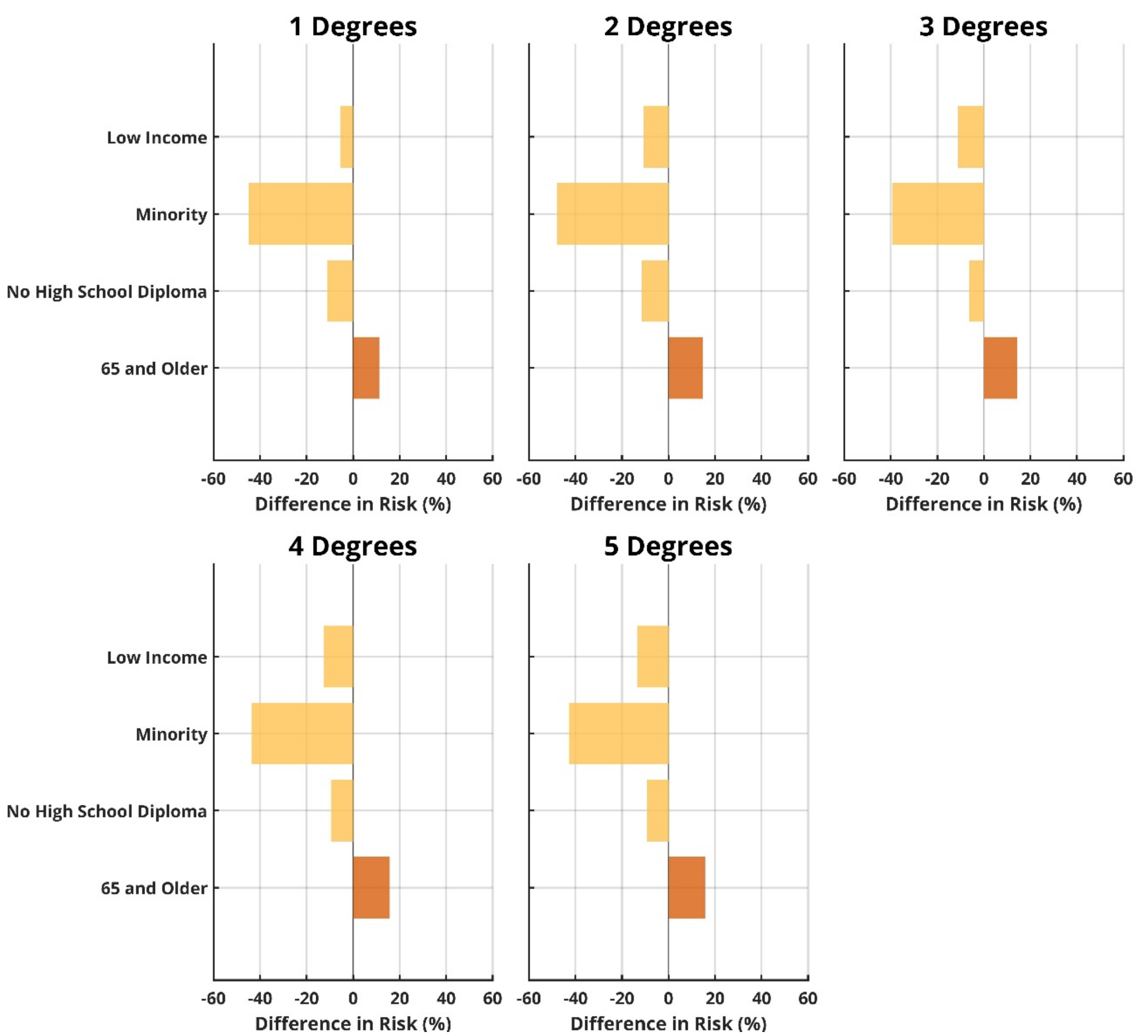


Figure 12. Likelihood that Those in Individual Racial and Ethnic Groups Live in Areas with the Highest Projected Traffic Delays from Climate-Driven Changes in Temperature and Precipitation, Relative to their Reference Populations (warming in °C)

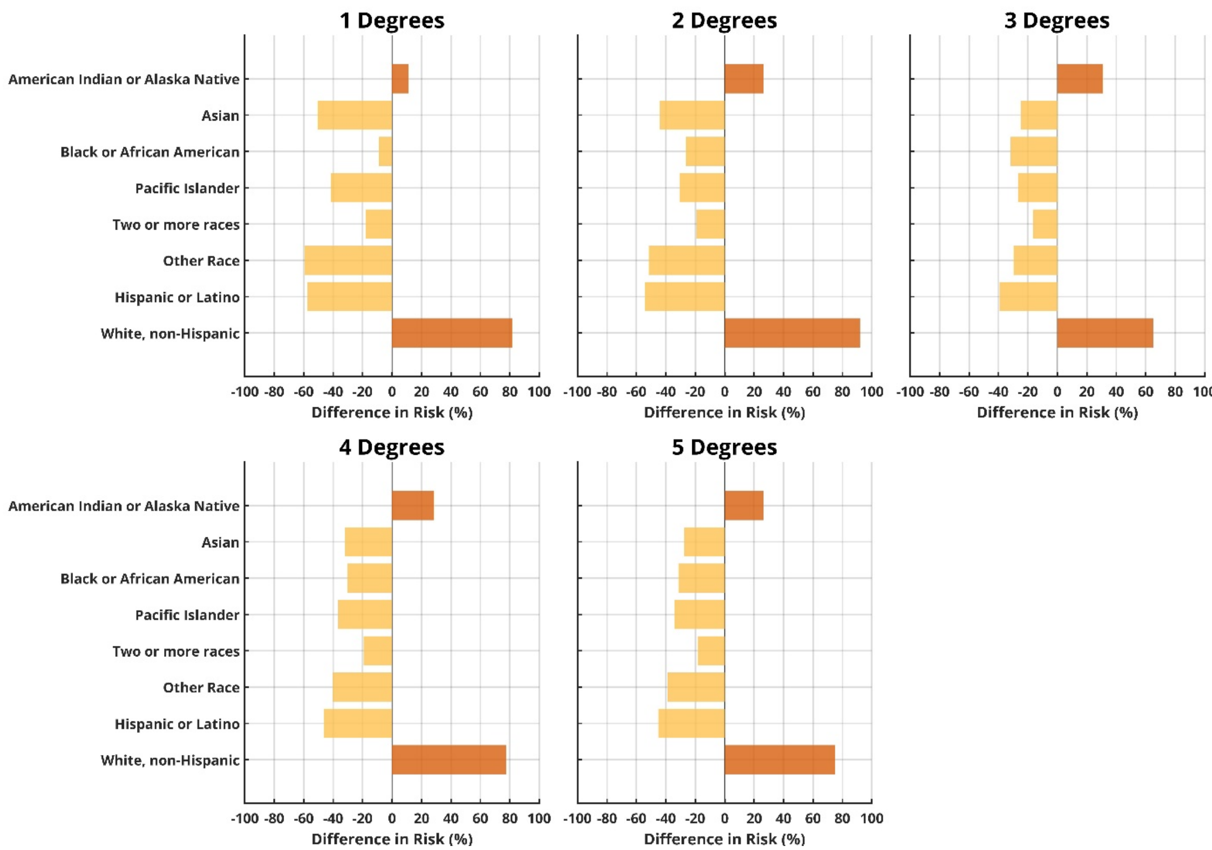


Figure 13 shows the projected difference in risk for the exclusion from adaptation metric, which focuses on areas that benefit the least from adaptation relative to the traffic delay risk without adaptation. Minority populations are projected to have low traffic delay risks compared to the reference population, but they benefit the most from adaptation at 1°C of warming. After 1°C, adaptation is relatively equally distributed across the socially vulnerable populations and the reference populations at the national scale, with virtually no meaningful disparities in outcome across socially vulnerable groups.

Figure 13. Likelihood that Those in Socially Vulnerable Groups Live in Areas with the Highest Rates of Exclusion from Adaptation to Changes in Temperature and Precipitation, Relative to their Reference Populations (warming in °C)

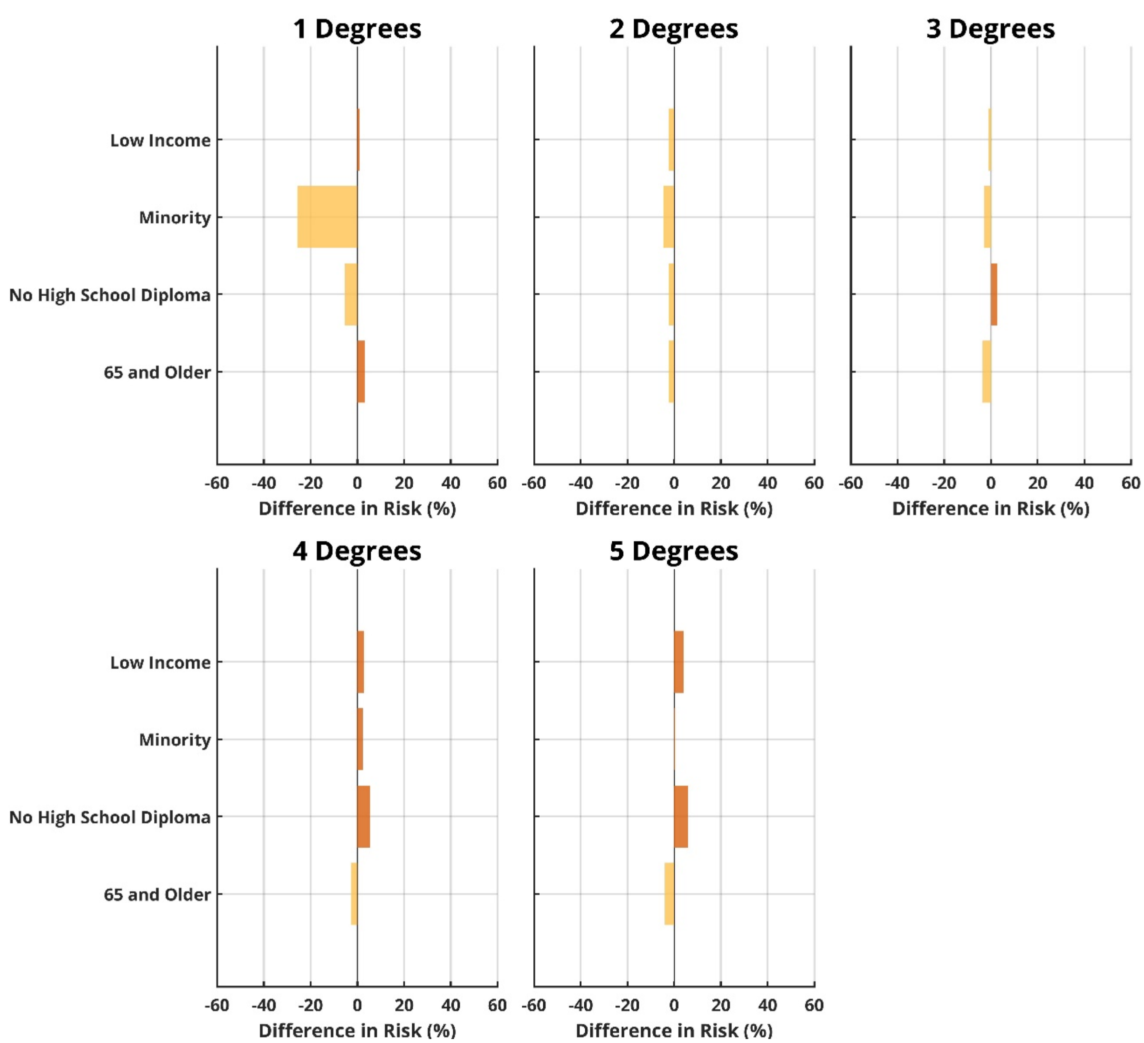


Figure 14. Likelihood that Those in Individual Racial and Ethnic Groups Live in Areas with the Highest Rates of Exclusion from Adaptation to Changes in Temperature and Precipitation, Relative to their Reference Populations (warming in °C)

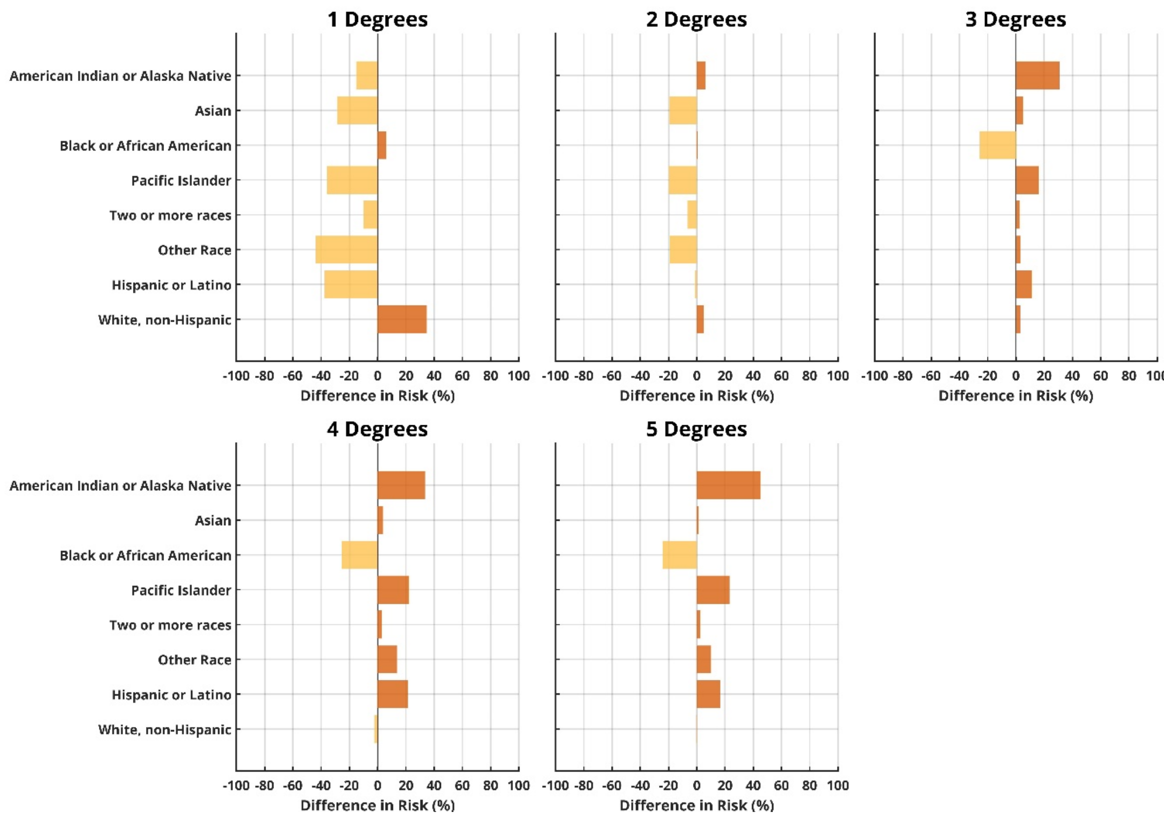
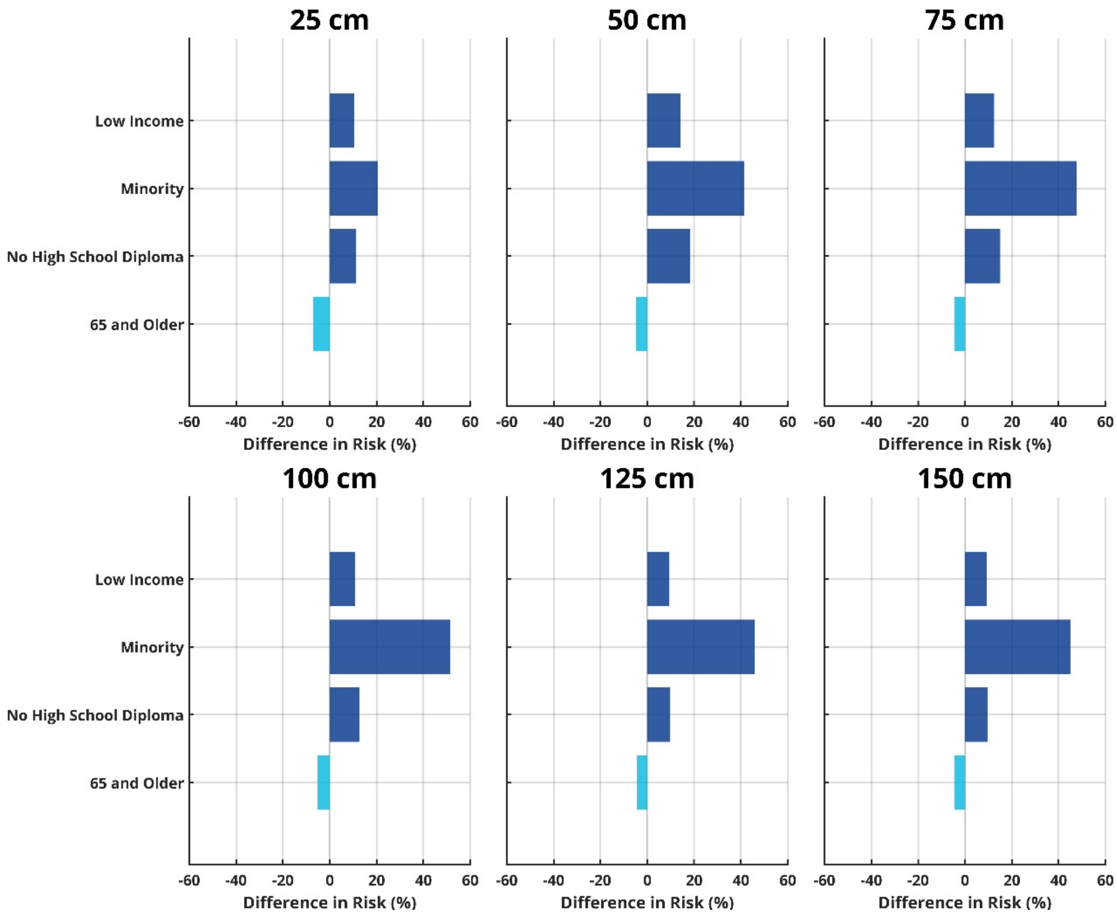


Figure 14 shows the projected difference in risk for the exclusion from adaptation for eight racial and ethnic populations compared the rest of the population. At 1°C of warming, most racial and ethnic populations will benefit from adaptation and White, non-Hispanic individuals are most likely to have higher delays under a scenario that included direct adaptation. Starting at 3°C, however, other racial and ethnic populations show a disproportional effect in risk. Most prominent are individuals who identify as American Indian or Alaska Native, who are projected to be 31% to 45% more likely to have remaining traffic delays after adaptation than the rest of the population. Since they are also more likely to have higher traffic delays (Figure 12), this indicates traffic delays for these populations may remain high even with proactive adaptation. Individuals who identify as Pacific Islander and Hispanic/Latino are also more likely to be excluded from adaptation at 3°C and above - they are also less likely to live in areas with the worst traffic delays (see Figure 12), which represents a more nuanced effect for these populations.

Figure 15. Likelihood that Those in Socially Vulnerable Groups Live in Areas with the Highest Projected Traffic Delays from Climate-Driven Changes in HTF, Relative to their Reference Populations (warming in °C)



High tide flooding traffic delays in coastal areas tends to impact different demographics than traffic delays from temperature and precipitation damage on roads. As indicated in Figure 15, traffic delay risk from HTF events tends to be higher in coastal areas for these populations. Minority populations are projected to be more than 40% more likely to be at risk of the worst impacts from HTF for all levels of SLR beyond 25 cm. The only socially vulnerable population projected to be less at risk are those 65 and older.

Figure 16. Likelihood that Those in Individual Racial and Ethnic Groups Live in Areas with the Highest Projected Traffic Delays from Climate-Driven Changes in HTF, Relative to their Reference Populations (warming in °C)

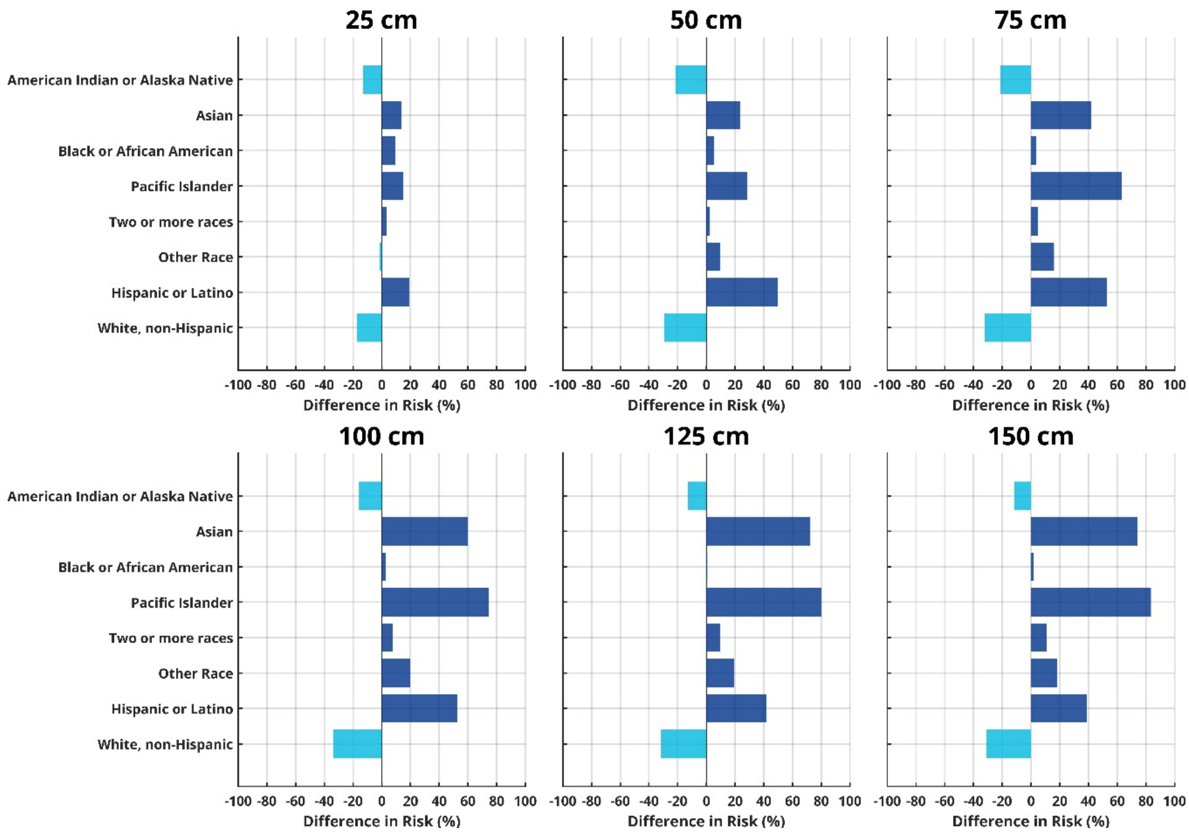


Figure 16 shows the difference in risk for eight racial and ethnic populations compared to the rest of the population for HTF events. The impacts are projected to be more evenly distributed at 25 cm, but at higher levels of sea level rise, the worst impacts from traffic delays disproportionately affect many socially vulnerable populations, particularly individuals who identify as Asian, Pacific Islander, and Hispanic/Latino. Starting at 75 cm, these three racial and ethnic populations are projected to be more than 40% more likely to live in areas with the worst traffic delays from HTF.

Figure 17. Likelihood that Those in Socially Vulnerable Groups Live in Areas with the Highest Projected Exclusion from Adaptation to Climate-Driven Changes in HTF, Relative to their Reference Populations (warming in °C)

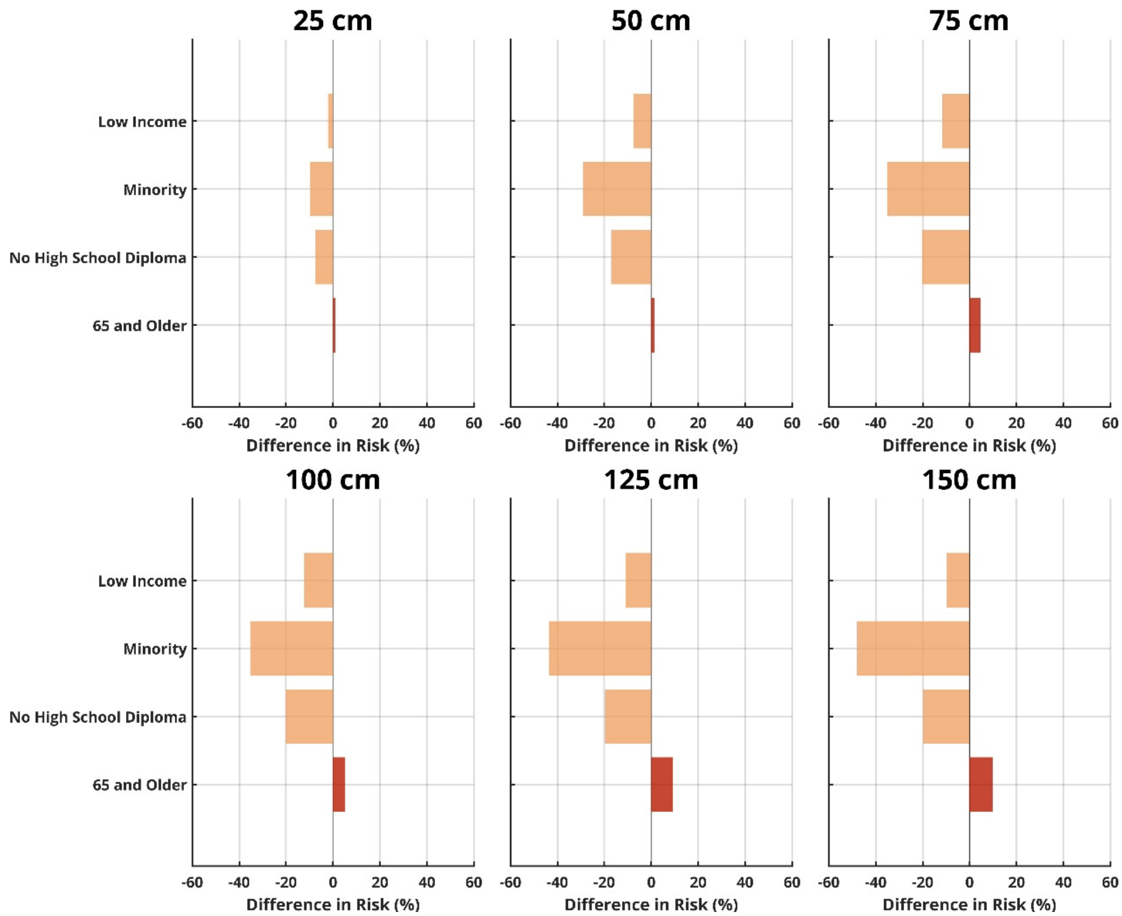
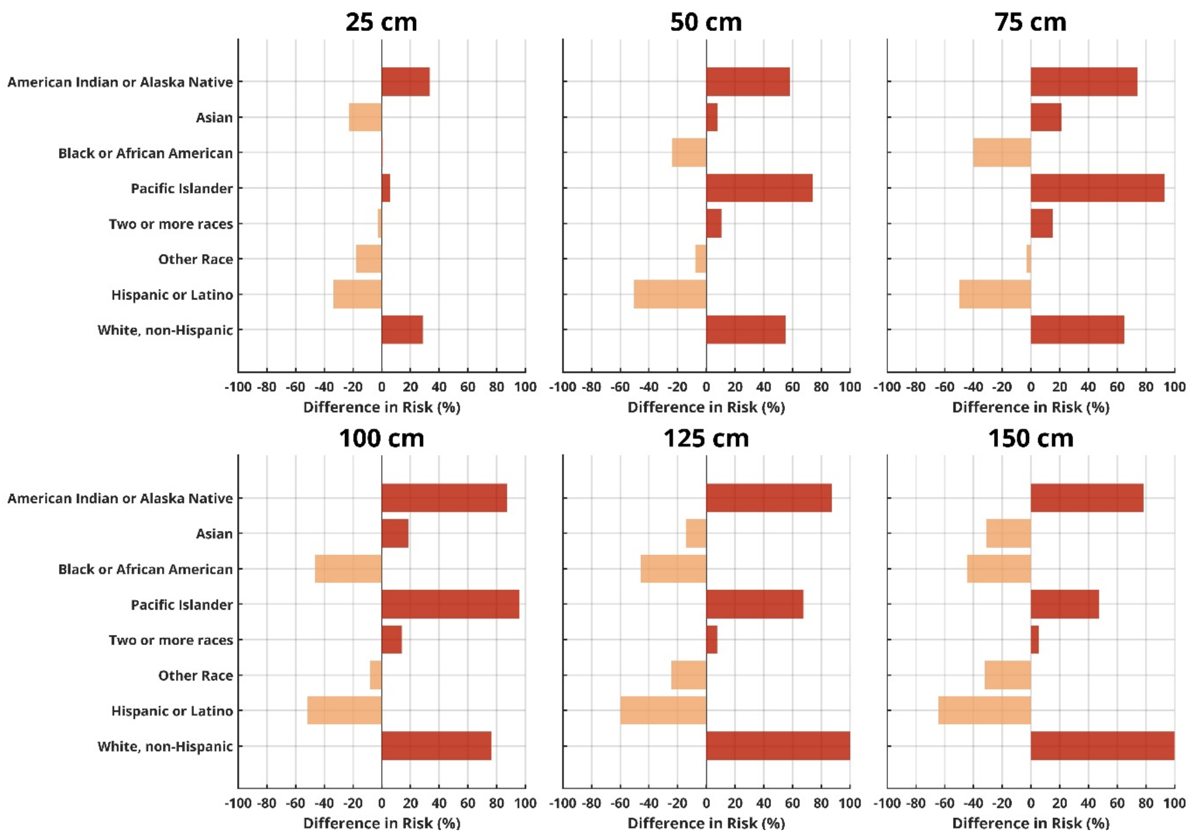


Figure 17 shows the projected exclusion from adaptation difference in risk for socially vulnerable populations compared to the reference population for HTF traffic delay. At 25 cm, individuals who live in low-income households are more likely to be excluded from direct adaptation, albeit only be a small margin. Since these individuals are also more likely to live in areas with a higher traffic delays at 25 cm, these populations may be particularly at risk without from the projected benefits of adaptation. Populations 65 and older are slightly less likely to live in areas with higher impacts (less than 10%), but they are also projected to be more likely to be excluded from adaptation (often over 20%). This indicates that these individuals who do have higher traffic delay risks may not have roads in their areas that pass a benefit-cost test for direct adaptation projects.

Figure 18. Likelihood that Those in Individual Racial and Ethnic Groups Live in Areas with the Highest Projected Exclusion from Adaptation to Climate-Driven Changes in HTF, Relative to their Reference Populations (warming in °C)



Although Figure 17 shows that minority populations, as a whole, are less likely to be excluded from adaptation, Figure 18 shows that is not the case for all categories of racial and ethnic populations. American Indian or Alaska Native individuals, as well as Pacific Islander individuals, are often projected to be over 60% more likely to be excluded from protection. Also, at certain sea levels, individuals who identify as Asian are more likely to be excluded from protection (50, 75, and 100 cm).

Regional Difference in Risk for Socially Vulnerable Populations

Regional differences in risk for socially vulnerable populations compared to the reference population are organized by social vulnerability categories. Regional results focus on the HTF results, and omit the temperature and precipitation results Figure 19 shows the difference in projected risk of traffic delays without adaptation from HTF events for low income populations. Compared to traffic delays from temperature and precipitation damage, HTF often shows the opposite difference in risk. The Northeast is the region with the highest projected difference in risk ranging from 32% to 36% at all levels. The Northwest is also notable with percentages higher than 20% at all temperatures. Compared to road damage from atmospheric conditions, traffic delays from HTF are highly localized. The Northeast and Northwest, however, are not among the regions with the highest absolute overall per capita delays (see Figures 7 and 9 above). Regions with higher traffic delays, like the Southern Plains and Southeast-

Atlantic, also indicate low income populations are more likely to be at risk, although to a lesser degree, between an estimated 9% and 13%, respectively.

Figure 20 shows the projected difference in risk for low income populations for the exclusion from HTF adaptation metric. For most of the regions, and even nationally, low income individuals are projected to benefit from adaptation about as much as everyone else, but there are a couple of notable differences. First, the Southern Plains show that low income populations are more likely to be excluded from simulated adaptation by about 18% at 50 cm. The Southern Plains is also the region with the highest impacts at 50 cm and one where lower income populations are more likely to be at risk. The second notable region is the Southeast-Gulf, where at 100 cm and above lower income populations are between 16% and 22% more likely to have higher remaining delays after adaptation.

Figure 19. Projected Relative Risk of Delay from HTF for Low Income

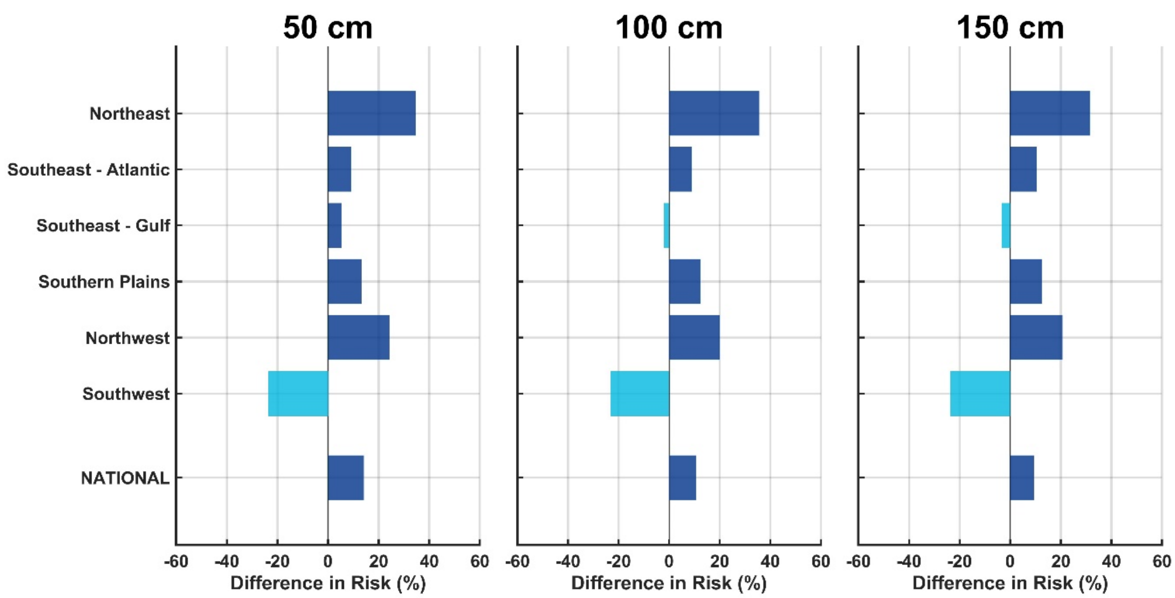
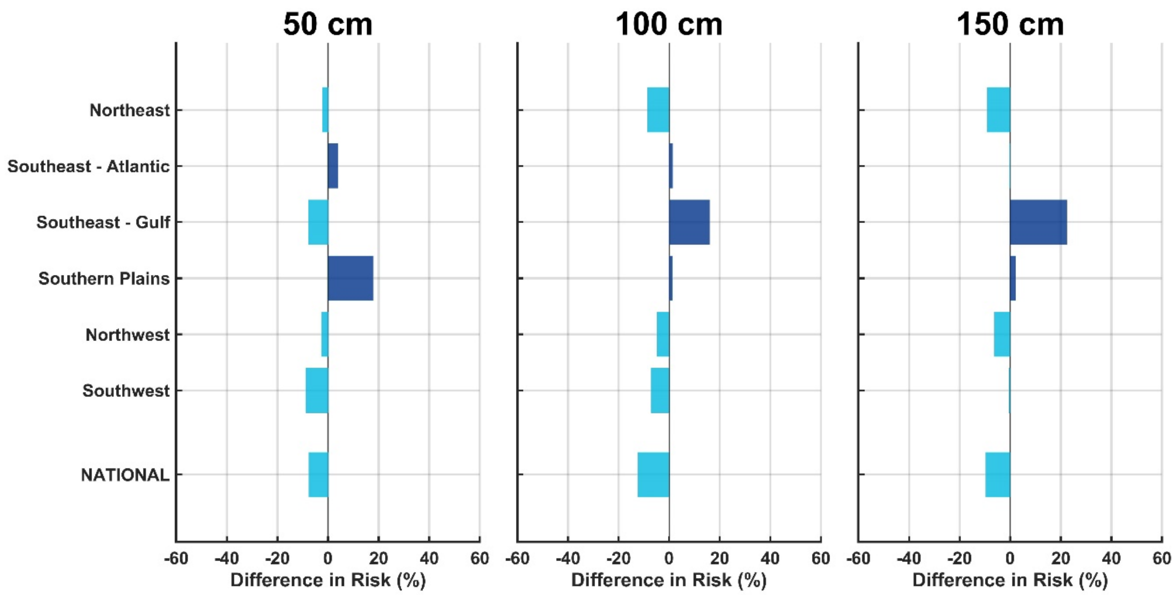


Figure 20. Projected Relative Risk of Exclusion from Adaptation from HTF for Low Income



Traffic delays from HTF events are shown in Figure 21. All coastal regions except the Southern Plains and Southwest indicate that minority populations are more likely, by 20% or more, to live in areas with the worst impacts. For the two coastal regions in the Southeast, minority populations are particularly at risk, between 30% to almost 40% more likely than White, non-Hispanic individuals.

The analysis further explores a least-cost rollout of adaptation for the roads exposed to HTF events, as shown in Figure 22. While minority populations are often more exposed to higher traffic delays, they are also more likely to benefit from direct adaptation. In fact, most regions and most levels indicate this is true, although there are a few exceptions. Projected results for the two Atlantic Coast regions show that minority populations are likely to benefit the most from direct adaptation while in the Northwest, adaptation is more equally distributed. Minority populations in the Southeast-Gulf at GMSL rise at and above 100 cm are both more likely to encounter the worst traffic delays from HTF and more likely to be excluded from simulated adaptation by 17% and 27% for 100 cm and 150 cm, respectively.

Figure 21. Projected Relative Risk of Delay from HTF for Minority Populations (in 50 cm increments of global mean sea level rise)

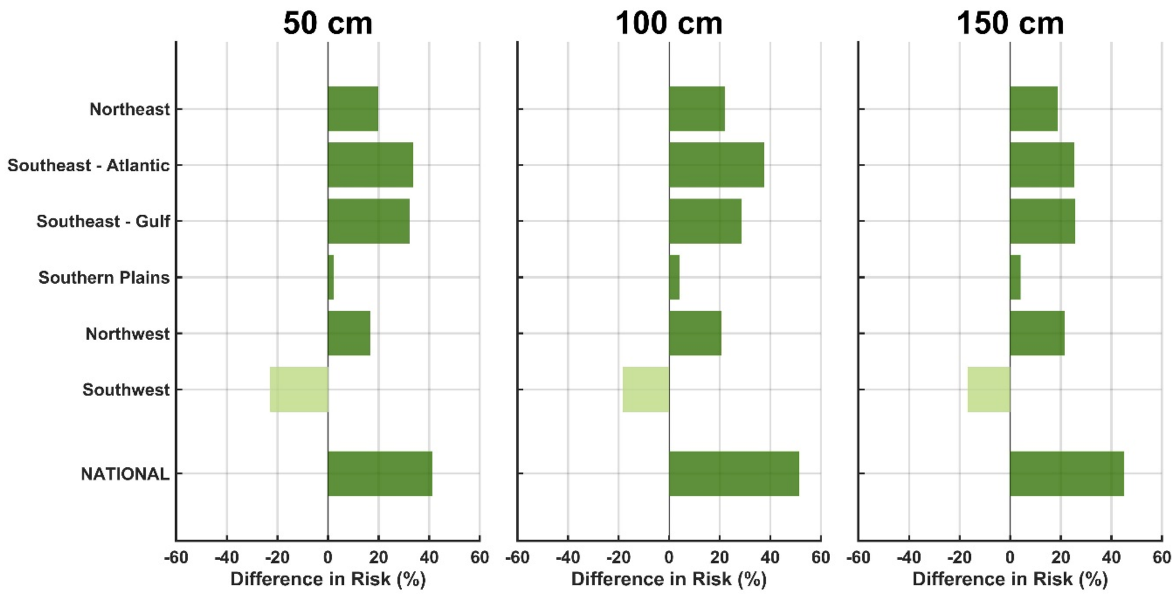
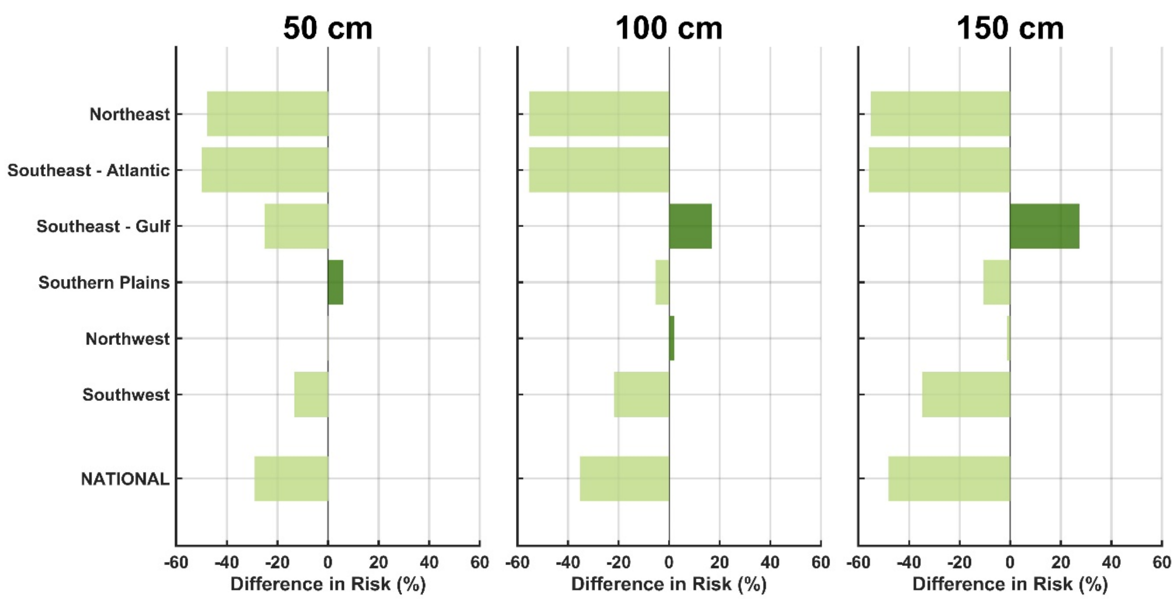


Figure 22. Projected relative Risk of Exclusion from Adaptation from HTF for Minority Populations (in 50 cm increments of global mean sea level rise)



Traffic delays from HTF events for adults with lower education attainment are shown in Figure 23. The region where these individuals are most likely to be at a higher risk than those with a high school diploma is the Northwest, but it is important to note that the Northwest is also projected to have the lowest traffic delay increases compared to other regions. These projected difference in risk for those without a high school diploma is over 40% at all levels of GMSL rise. The difference in risk for these individuals is also higher in the Northeast and Southeast-Atlantic, but less likely in the Southwest, which is the region with some of the highest impacts from traffic delays. These populations in the Southwest are also less likely to be excluded from adaptation, and so benefit more from adaptation as shown in Figure 24. The analysis shows that although adults without a high school diploma are more likely to encounter higher impacts in the Northeast and Southeast-Atlantic, they are less likely to be excluded from adaptation by about the same degree. These findings indicate the need for direct adaptation on roads in these regions to reduce these disproportionate risks.

Figure 23. Projected Relative Risk of Delay from HTF for Adults without a High School Diploma (in 50 cm increments of global mean sea level rise)

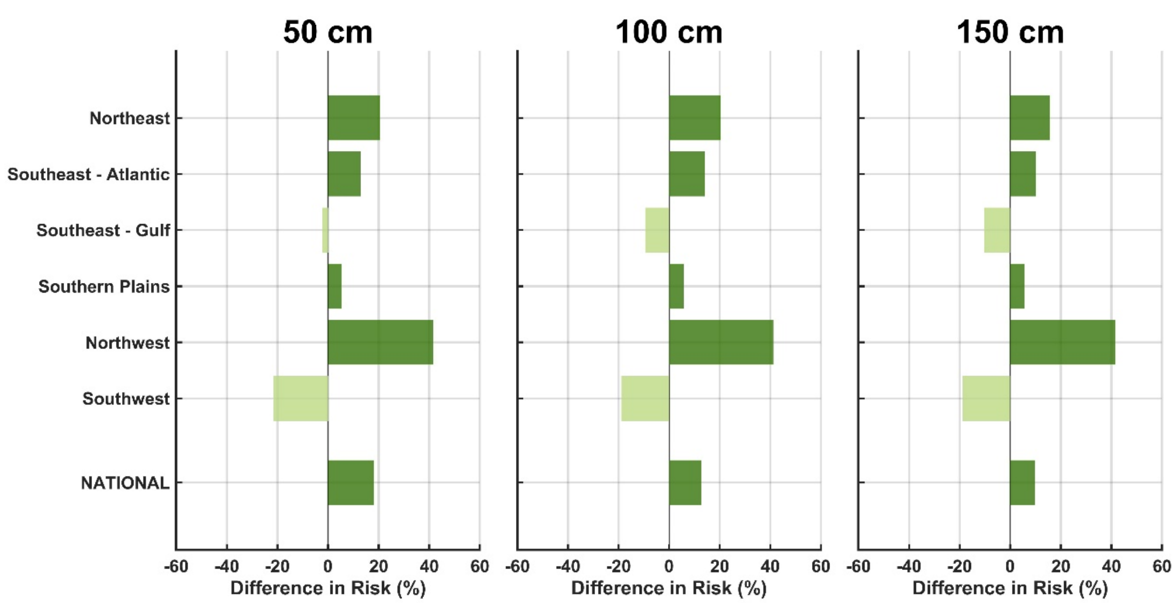


Figure 24. Projected Relative Risk of Exclusion from Adaptation from HTF for Adults without a High School Diploma (in 50 cm increments of global mean sea level rise)

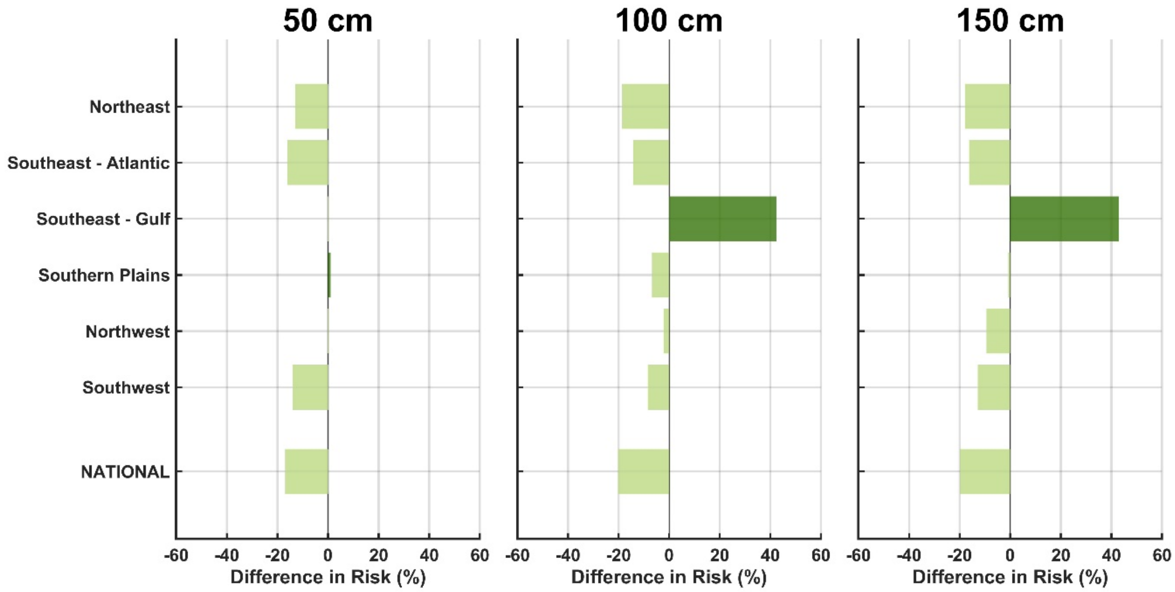


Figure 25 shows the differences in risk for those 65 and older from HTF traffic delays and Figure 34 shows the exclusion from adaptation. For most regions, people 65 and older are not projected to be at a particularly larger risk of exposure to increases in traffic delays. The Southwest does show a moderate difference in risk for these individuals at 9%-13%. The Southwest is also the region with some of the largest median increases in projected traffic delays, particularly for 100 cm and higher. Those 65 and older in the Southwest are also more likely to be excluded from protection at 100 cm and above by about 20%, putting these individuals at a particularly high risk. The Northeast and Southern Plains also indicate that people 65 and older are less likely to benefit from adaptation, as they are often (across the different sea levels) about 20% more likely to be excluded from adaptation benefits. People 65 and older in the Southeast-Gulf are projected to be more likely to benefit from direct adaptation decisions with exclusion from adaptation reaching -22% and -24% for 100 cm and 150 cm.

Figure 25. Projected Relative Risk of Delay from HTF for 65 and Older (in increments of 50 cm of global mean sea level rise)

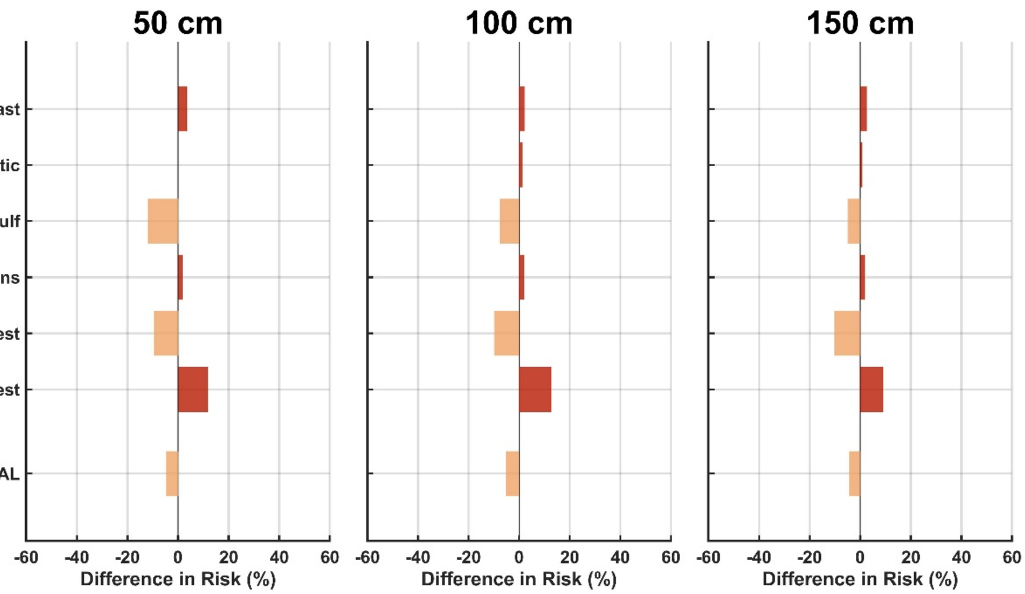
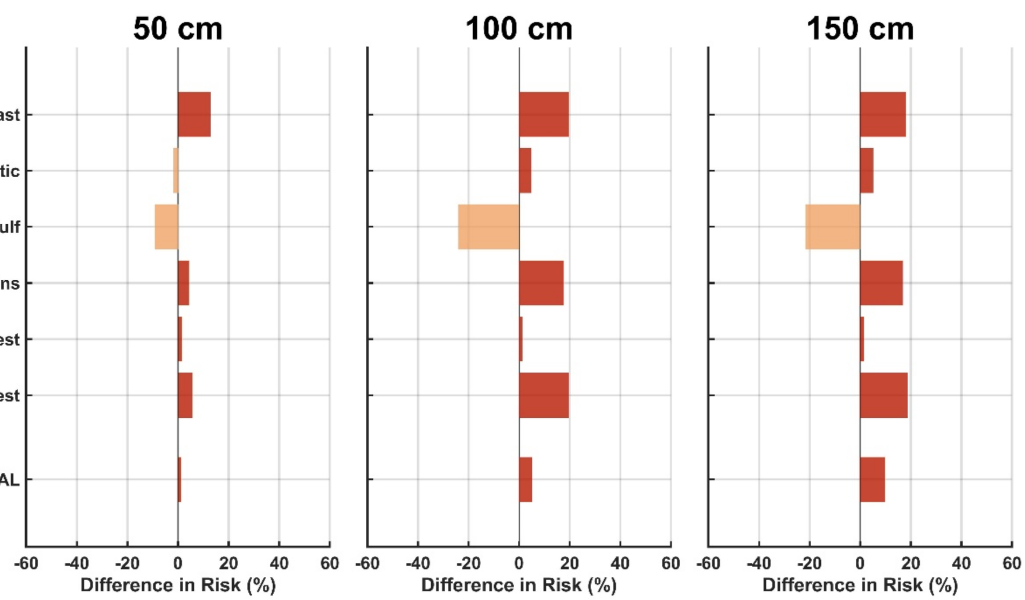


Figure 26. Projected Relative Risk of Exclusion from Adaptation from HTF for 65 and Older (in increments of 50 cm of global mean sea level rise)



7. Limitations

The following section lists major limitations in the analyses of this Roads section. See Neumann et al.[22] and Fant et al.[26] for additional descriptions of limitations from the two analyses.

General limitations that apply to both analyses

- This analysis quantifies the first-order effects of transport delays as a loss in available time. Secondary impacts, such as lost productivity in multiple economic sectors, are not estimated.
- Roads are not the only transportation mode in the U.S., although it is by far the most common. Those who do not travel long distances or use other forms of transportation, such as underground passenger rail or walking, would not directly encounter these impacts.
- Construction delays are likely to vary by project. This analysis uses national average construction delay times from RSMeans,[33] which may vary by region. Similarly, costs for adaptation and road maintenance likely vary due to local factors. For costs, this analysis also relies on national average material and labor costs from RSMeans.
- In both analyses, the road network itself and traffic volumes are assumed to remain static over time. Since some of these climate effects are likely to occur in the future up to the end of the century, the transportation sector may see significant changes (e.g., volume of passengers, technology) over that time.

Limitations specific to temperature and precipitation road damage impacts on traffic delays

- For this analysis, roads are generalized into three categories of surface material (paved, gravel, and unpaved) and three function levels (primary, secondary, and tertiary). Site-specific characteristics, as well as road design and construction practices that differ by area may change the way in which precipitation and temperature damage roads and how that damage influences traffic delays. These location-specific parameters are not captured in this national-scale analysis.
- Traffic delays caused by increased road surface roughness are generalized for use in this national-scale analysis, and based on changes to free-flow speed. While surface roughness does impact speed for most vehicles, the effect will vary by vehicle and driver.
- There is a need for more rigorous exploration of climate-related stressors beyond temperature and precipitation, which could include wildfires and dust storm effects on visibility and transport delays, in addition to the potential for winter events to moderate or, in some contexts, worsen. This analysis omits winter road clearing and maintenance costs, for example, which may present an overestimation bias, as winter season costs are likely to moderate with higher temperatures.
- Other atmospheric parameters such as wind speed, humidity, and cloudiness may affect road safety and delays. These are likely to be secondary to temperature and precipitation, which have been more extensively studied and shown to affect road integrity and delays.

Limitations specific to high tide flooding impacts on traffic delays

- This study was limited in the site-specific information available, which prevented investigation of effects such as direct damage to the road infrastructure from flooding, an effect explored on a case-study basis only in Fant et al.

[33] Gordian. 2019. Heavy Construction Costs with RSMeans Data 2019. Transportation.

- The analysis is limited to road segments within the NOAA-estimated flood extent for the current minor flood level. Sea level rise will expand this extent, and additional roads will become vulnerable with higher sea levels, likely causing more delays and road damage than determined in this study. Fant et al.[26] estimates that total vulnerable traffic could increase by about half in 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. In a general sense, technological, behavioral, and financial barriers stand in the way of achieving an economically optimal adaptation outcome. Some of these are listed below
    - *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. Also, additional costs associated with managing road closures and detours are not considered. However, the analysis also does not calculate time value effects associated with potentially longer travel times following rerouting, which in some coastal areas can be substantial, and could lead to underestimation of road delays.
    - *Ancillary protection:* to take full effect, homeowners and communities would need to protect properties from SLR and storm surge risk at the right time and location – but Lorie et al.[34] among others suggest decisions to invest in coastal property protection are suboptimal – and there is also a risk that coastal protection has less than 100% efficacy in protecting adjoining roads.
    - *Direct adaptation:* raising road profiles and constructing sea walls are modeled as an incremental cost during the “next” major rehabilitation cycle. Adding a road raising option to these projects may complicate the permitting and execution of rehabilitation, which may happen on a longer than 20-year time cycle (extending delay time) and may involve further complications, such as raising or protecting nonvehicular infrastructure (e.g., above and below ground utilities, stoplights, sidewalks). All of these could substantially raise the cost of direct adaptation.
- Precipitation and river flooding may prolong traffic delays caused by high tide flooding events. The combined effects of tidal and precipitation-induced flooding 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.

[34] Mark Lorie, James Neumann, Marcus Sarofim , Russell Jones, Radley Horton, Robert E. Kopp, Charles Fant, Cameron Wobus, Jeremy Martinich, Megan O’Grady (2020) Modeling Coastal Flood Risk and Adaptation Choices under Future Climate Conditions, Climate Risk Management, Vol 29, 100233. https://doi.org/10.1016/j.crm.2020.100233

8. Data Sources

NAME	DESCRIPTION	DATA SOURCE(S) AND/OR EPA DISSEMINATION PLAN
Infrastructure Roads Data	*Precipitation and temperature impacts:* Using state-level roads data from U.S. Department of Transportation (DOT) (2008) and digitized road maps from Tele Atlas (2003), the lane miles of paved and unpaved roads are estimated for a series of 0.5 by 0.5 degree grid cells.	*Precipitation and temperature impacts:* Road inventory is described in Chinowsky P, Price J, Neumann J. 2013. Assessment of climate change adaptation costs for the U.S. road network. Glob Environ Chang, 23 (4):764-773. See U.S. Department of Transportation, Federal Highway Administration, 2009. Highway Statistics 2008, October 2009 and Tele Atlas, 2003. 2003 Tele Atlas Dynamap Transportation, Version 5.2 Product.
	HTF impacts: Highway Performance Monitoring System (HPMS) shapefile data from 2016 are used, and 2015 data for the roads and bridge locations. Roads data processes for each coastal state based on the methods outlined in Jacobs et al. (2016). Separate analyses were performed for functional classes 1-2 and 3-7.	*HTF impacts:* HPMS shapefile data were downloaded from the HPMS Public Release of Geospatial Data website for each state, https://www.fhwa.dot.gov/policyinformation/hpms/shapefiles.cfm
Traffic and Ridership Data	*Precipitation and temperature impacts:* Road traffic from the DOT Freight Analysis Framework Network for paved primary and secondary roads and includes truck traffic. Derived estimates of traffic for tertiary roads using data from FHWA (2013) on average annual daily traffic (AADT).	*Precipitation and temperature impacts:* U.S. DOT. 2017b. Freight Analysis Framework Network. Downloaded from http://osav-usdot.opendata.arcgis.com/datasets/560e1c2711f34aaf904fd8ab1f9333b9_0 and FHWA. 2013. Highway Functional Classification Concepts, Criteria and Procedures. 2013 Edition. U.S. Department of Transportation, Federal Highway Administration.
	HTF Impacts: The HPMS spatial data contained data on the AADT, lane width, and surface type. These data are used in various parts of the analysis, including the traffic delay estimation, the road redundancy calculation, and the direct costs, respectively.	*HTF Impacts:* U.S. DOT Federal Highway Administration. 2016. Highway Performance Monitoring System Field Manual. Control No. 2125-0028
National Coastal Property Model (NCPM)	The National Coastal Property Model was developed in order to estimate coastal flood damages in the U.S. as a result of different sea level rise and storm surge scenarios. The model estimates flood and inundation damages, as well as the cost of investments in coastal protection. The model was used to designate roads protected from actions to protect property (Ancillary Protection).	Neumann, J. E., Hudgens, D. E., Herter, J., & Martinich, J. (2010). Assessing sea-level rise impacts: a GIS-based framework and application to coastal New Jersey. *Coastal management*, 38(4), 433-455. Neumann, J. E., Emanuel, K., Ravela, S., Ludwig, L., Kirshen, P., Bosma, K., & Martinich, J. (2015). Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy. *Climatic Change*, 129(1-2), 337-349. Lorie., M, et al. (2020). Modeling Coastal Flood Risk and Adaptation Response under Future Climate Conditions. *Climate Risk Management*, 29:100233, https://doi.org/10.1016/j.crm.2020.100233

NAME	DESCRIPTION	DATA SOURCE(S) AND/OR EPA DISSEMINATION PLAN
Coastal Flood Exposure Map	Raster datasets containing the extent of the flood at the minor level for each state were provided by NOAA and used to determine which road segments are vulnerable to tidal flooding.	National Ocean Service, Office of Coastal Management (2019). Coastal Flood Exposure Mapper. National Oceanic and Atmospheric Administration. www.coast.noaa.gov/floodexposure/ Accessed May 2019.
Sea Level Rise scenarios	Sea level projections for U.S. coastlines produced for the Fourth National Climate Assessment at a 1 degree spatial resolution and a decadal temporal resolution.	Sweet, W. V., Kopp, R. E., Weaver, C. P., Obeysekera, J., Horton, R. M., Thieler, E. R., & Zervas, C. (2017). Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083.
Tide gauge data	Hourly water levels from tide gauge stations were obtained from NOAA's Center for Operational Oceanographic Products and Services (NOS 2019) and methods for analysis are described in Sweet et al. (2018). 83 tide gauges from this set are in the U.S. Analysis uses 19-years of hourly water levels spanning from 1999 to 2017.	Sweet, William, Greg Dusek, Jayantha Obeysekera, John J. Marra (2018) Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS 086.
Welfare Economic Cost of Traffic Delays	Different sources were used for passenger and freight vehicles. For passenger vehicles, the approach follows that recommended in U.S. DOT (2016b) To quantify the cost of delay for freight vehicle travel, this analysis relies on data from the National Cooperative Highway Research Program (NCHRP) that are used as inputs to their Truck Freight Reliability Valuation Model (NCHRP 2016).	Passenger vehicles: U.S. DOT. 2016b. *Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis*. Downloaded from https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf Freight vehicles: Methodology for Estimating the Value of Travel Time Reliability for Truck Freight System Users, document available along with Excel-based Truck Freight Reliability Valuation Model and User's Guide at: http://www.trb.org/Publications/Blurbs/174297.aspx