Climate Change

INTRODUCTION & CONTEXT

There is broad consensus that climate change will alter the natural environment, economy, and quality of life in Minnesota over the next century and beyond, though specific impacts remain uncertain. Increased temperature variation, precipitation levels, and frequency of extreme weather events are expected to stress the transportation system's design, construction, maintenance, and operations, and will generally increase the lifecycle costs of infrastructure. To maintain security and enhance financial effectiveness over the next 20 years, it will be critical to integrate consideration of climate vulnerability into transportation planning and investments.

While climate change is a global phenomenon, its effects have been particularly acute in Minnesota, where annual average temperatures have risen two degrees over the past century, 25 percent more than the global average, and up to three degrees in the northern part of the state. Minnesota's winter temperatures have risen more than that of any other state over the past 40 years. In addition to greater temperature rises, Minnesota has experienced more large storms.[1] Many of Minnesota's diverse ecosystems are particularly sensitive to a changing climate. Species at the edges of these ecosystems will be most vulnerable to climate change.

Within transportation and infrastructure planning, climate change mitigation and adaptation activities are often conflated, though they have distinct goals. Mitigation focuses on reducing greenhouse gas emissions in order to manage the magnitude of future climate change. Adaptation focuses on bolstering the resilience and reducing the vulnerability of the transportation system to hazards generated by a changing climate. Important trends to track related to climate change adaptation include the evolution of international, federal, and state policy, climate data and modeling, cost-benefit analysis, long range planning of transportation and land use, asset management, and new approaches to maintenance and operations.

MITIGATION

In 2007, the Minnesota Legislature passed the Next Generation Energy Act that set a goal of reducing Minnesota's greenhouse gas emissions 80 percent below 2005 levels by 2050 with targets of a 15 percent reduction by 2015 and a 30 percent reduction by 2030. The following year, the Legislature established a specific goal of reducing greenhouse gas emissions from the state's transportation sector.[2] In October 2015, Governor Dayton signed a global memorandum of understanding on behalf of the state committing the state to work toward limiting the global average temperature from increasing more than 2 degrees Celsius.

Since 2005, greenhouse gas emissions from the transportation sector in Minnesota have declined and are projected to continue declining through 2030. Figure 1 shows historical and projected transportation emissions from all sources from 1990 to 2030. While transportation emissions are projected to decrease between now and 2030, they are still projected to be 10-15 percent higher than the 30 percent reduction from 2005 levels Next Generation Energy Act target.

[1] Climate Change in Minnesota: an MPR News Special Report (2015)

[2] MN State Statute Chapter 287

Figure 1: Historical and projected transportation sector greenhouse gas emissions in Minnesota

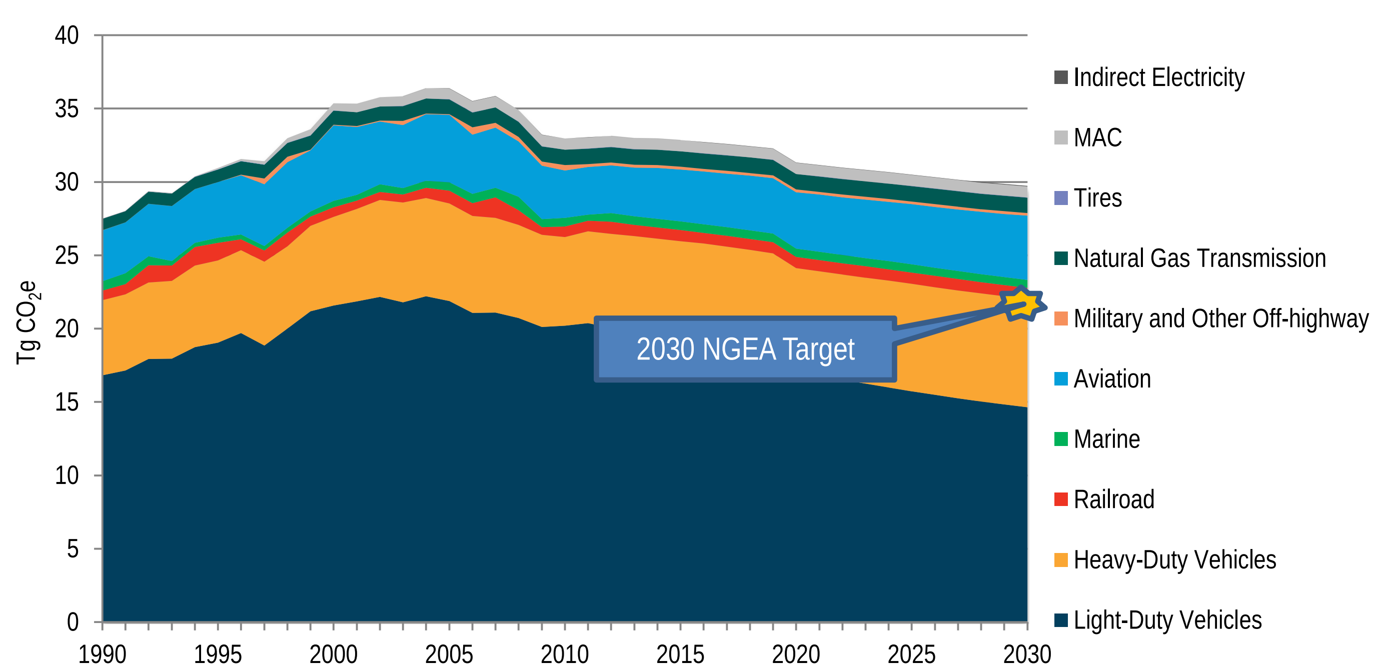
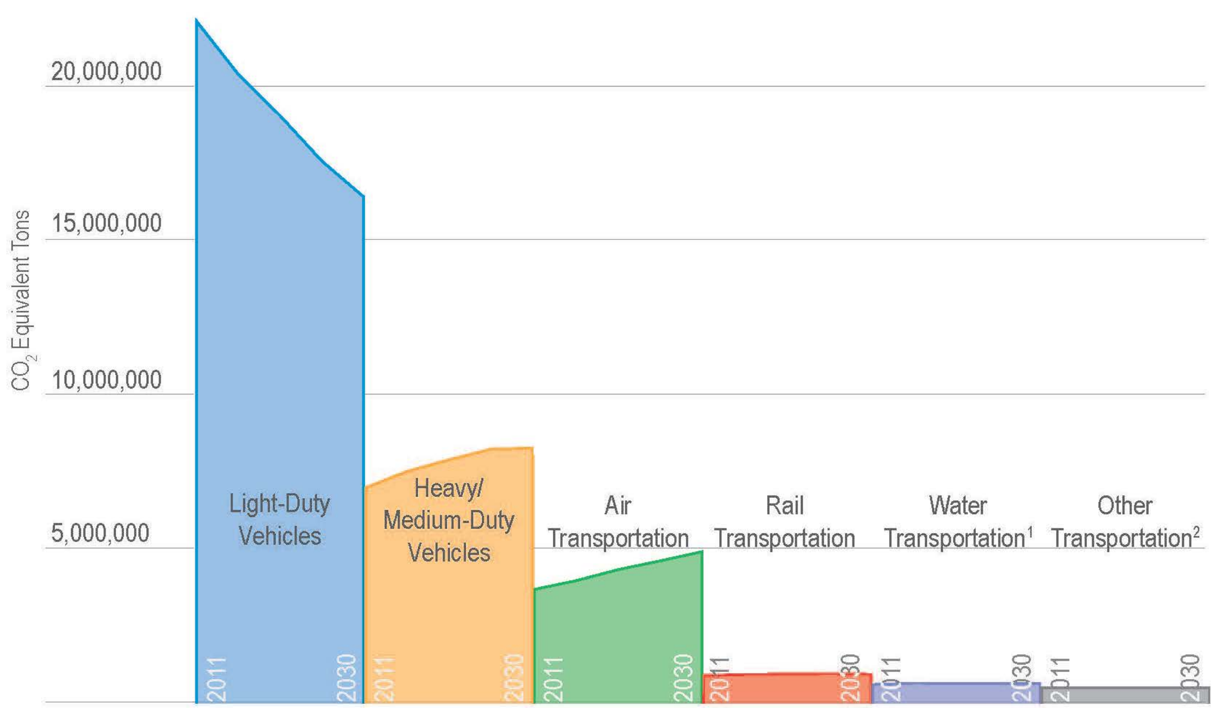


Table note: Tg=million metric tons / source MPCA

The majority of the emission reductions are the result of slowing growth and reduction in vehicle miles travelled from 2005 through 2012 and increased vehicle efficiency driven by the federal CAFE standards. Increasing efficiency of light duty vehicles is projected to increase, but emissions from both medium and heavy duty vehicles as well as air transportation are projected to increase over the next 15 years (see Figure 2).

Figure 2: Forecasted greenhouse gas emissions by transportation mode, 2011 - 2030



1: Water transportation includes lake shipping, barge, and recreational marine travel.
2: Other transportation includes emissions from tires and lubricants, military transportation, and miscellaneous off-highway travel.

ADAPTATION

Adaptation involves actions to reduce vulnerability and increase resilience of the transportation system in anticipation of climate change and associated extreme weather events.[3] Adaptation can thus reduce the impacts of climate-related stresses (longer-term trends that increase vulnerability) and shocks (extreme weather events).

Adaptation considerations can be incorporated into asset management, long range transportation planning, design and construction, operations and maintenance, and emergency management. Adaptation is usually informed by vulnerability assessments, though the two are distinct processes.[4]

The U.S Department of Transportation's policy statement on climate change adaptation provides these guiding principles:[5]

- Adopt integrated approaches, prioritize the most vulnerable
- Use best-available science
- Build strong partnerships
- Apply risk-management methods and tools
- Apply ecosystem-based approaches
- Maximize mutual benefits, and continuously evaluate performance

Currently, state DOTs, MPOs, local planning agencies, and federal land management agencies may use federal-aid highway funds for vulnerability and risk assessments for federal-aid highways related to climate change and extreme weather.[6]

Vulnerability and Climate Risk

In terms of transportation vulnerability, FHWA defines transportation system vulnerability to climate change as including three components:

- Exposure: The degree to which an asset may be affected by a climate stressor.
- Sensitivity: How well an asset impacted by a climate stressor is able to cope with the impacts.
- Adaptive Capacity: How resilient the transportation system as a whole is if the asset were to be taken out of service.

CLIMATE STRESSORS AND HAZARDS

Future projections of climate hazards involve a high level of uncertainty, because they are based on global models that are difficult to downscale, and are thus most appropriately interpreted over large geographic areas such as the entire Midwest region. Extreme weather and variability has always been a part of Minnesota's climate history, because of the state's geographic location at a convergence of air masses from the polar Arctic (cold), the Gulf of Mexico and Southwestern U.S (warm), and the Pacific Ocean (mild and dry). Among extreme weather events, precipitation and storm events are particularly difficult to model at the regional or local scale. Generally, extreme weather events such as flooding and heat waves are likely to become more acute in the southern half of the state , while the north has the highest level of ecosystem sensitivity to climate change.[7]

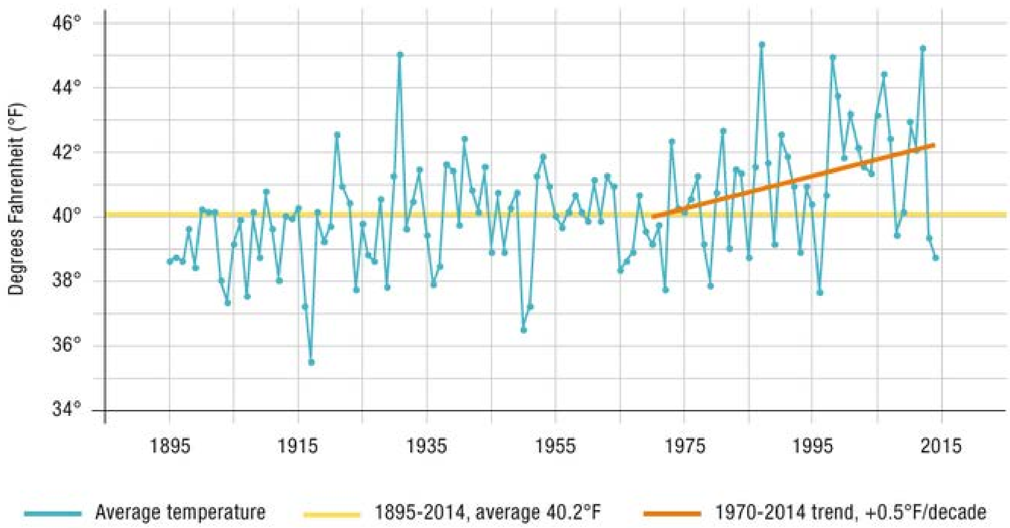
Temperature

From 1895-2013, average temperatures have risen, most dramatically in January (2.5-4.5 degrees of warming), February (5-7 degrees), and March (3-5 degrees). Global climate models predict annual average temperature increase of 4.8-5°F throughout the state.[8] Analysis combining global

[3] TRB, 2014. Climate Change, Extreme Weather Events, and the Highway System.
[4] FHWA, 2013. Assessment of the Body of Knowledge on Incorporating Climate Change Adaptation Measures into Transportation Projects.
[5] US DOT, 2011. Policy Statement on Climate Change Adaptation.
[6] FHWA, 2012. Eligibility of Activities To Adapt To Climate Change and Extreme Weather Events Under the Federal-Aid and Federal Lands Highway Program
[7] MDH, 2014. Minnesota Climate Change Vulnerability Assessment.
[8] Adapting to Climate Change in Minnesota: 2013 Report of the Interagency Climate Adaptation Team

climate models with historical climate data estimates that Minnesota temperatures may increase by 6-10°F in the winter, and 7-16°F in the summer, resulting in a growing season that may be 3-6 weeks longer by 2100.[9] Increasing temperatures will decrease the number of days of ice cover on Lake Superior, which will make shoreline more vulnerable to erosion and flooding, and also extend the season for commercial navigation. Rising temperatures are also driving biome migration and the proliferation of insect pests through milder winters.[10]

Figure 3: Minnesota's Average Annual Temperature, 1895-2014[11]

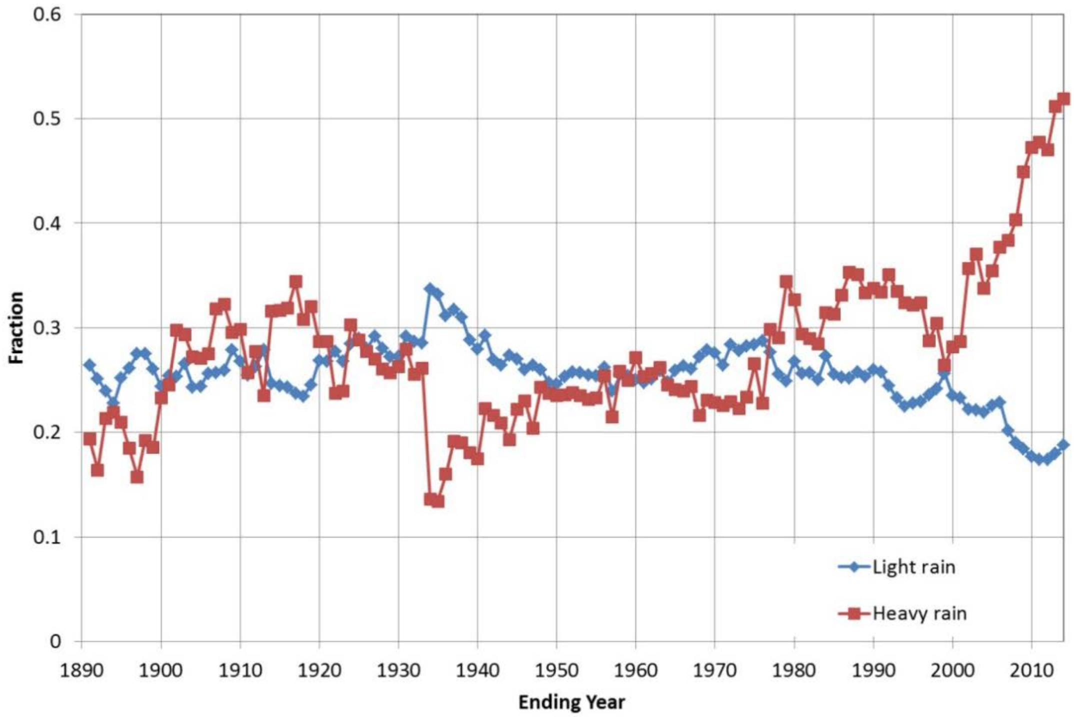


Precipitation

Minnesota has always had large storms. Historically, 2-inch rain events have occurred every five years for any given place throughout the state. However, the frequency of and intensity of heavy precipitation has increased within Minnesota, and the frequency of heavy rain events is expected to double by 2100.[12] Since 1860, Minnesota has had twelve so-called "mega-rain" events where at least six inches of rain falls on an area larger than 1,000 square miles—five have occurred since 2000. Over the last century the frequency of heavy rain events in Minnesota has increased while smaller rain events are less frequent (see Figure 4).

[9] Impacts of Climate Change on Northern Ecosystems (Johnson 2004, data derived from Wuebbles & Hayhoe 2004)
[10] MDH, 2015. Minnesota Climate and Health Profile Report: An Assessment of Climate Change Impacts on the Health & Well-Being of Minnesotans.
[11] Graph from MPR, 2015. Climate Change in Minnesota: 23 Signs.
[12] Impacts of Climate Change on Northern Ecosystems (Johnson 2004, data derived from Wuebbles & Hayhoe 2004)

Figure 4: Twenty-year rolling average of heavy rains (more than 1.45") and light rains (less than 0.41")



While annual precipitation between 2000 and 2013 has varied greatly, the average land area of the state classified as abnormally dry or drought-affected has increased. This is too short a time period to derive statewide drought trends, which is made more challenging because there are few measurements of drought-related variables. Historically, droughts have been more common in southwest Minnesota compared to the Northeast.[13] Rising winter temperatures suggest an increase in winter ice.

Flooding

Increased flooding frequency is a major concern, because of the acute damage flooding events can cause to infrastructure. Flooding is the most expensive natural disaster in the world ($40 billion in average annual losses)[14], and nationwide the average 100-year floodplain is expected to grow 45% and annual damages increase by $750 million by 2100. The types of flooding that will increase most in frequency include "localized floods," where rainfall overwhelms the capacity of drainage systems, and "riverine floods," where rainfall causes river flows to exceed the capacity of the river channel.[15]

13 Minnesota Hazard Mitigation Plan (2014)

14 A Flood of Benefits – Using Green Infrastructure to Reduce Flood Risk

15 Environmental Protection Agency, 2015. Build Green Infrastructure to Manage Flood Risk

Table 1: Summary of Climate Impacts and Transportation Outcomes in Minnesota

Climate Impact	Confidence in change for MN during next 20 years	Effect to Transportation System
Heavy Precipitation / Flooding	Very High	• Damage to highway, rail infrastructure, hydraulics infrastructure, airport runways • Overtopping roads will slow operations and performance.
Warmer Winters	Very High	• More ice • Reduced pavement conditions and life cycles • Downed power lines with ice storms • Reduced ice cover on water bodies leading to greater rates of evaporation
New species ranges	High	• Changes in roadside vegetation mixes • Soil erosion • Increase in invasive species populations • Increased exposure of construction and maintenance crews to vector-borne diseases
Drought	Medium	• Reduced river navigability for barges. • Stress roadside vegetation, which may reduce rainwater storage and increase soil erosion in the long-term.
High Heat	Low	• Pavement and rail buckling • Vehicles overheating • Electrical system malfunctions • Limitations on construction hours
Wildfires	Unknown	• Road closures • Immediate and significant threat to human safety • Damage to roadside infrastructure

DATA ANALYSIS AND MODELLING

Data limitations of both asset inventories and regional climate conditions pose a significant barrier to advancing risk-based adaptation planning and evaluation.[16] The global scale of climate change models limits their ability to predict climate trends at smaller geographic scales. Even statewide predictions for Minnesota carry a high level of uncertainty regarding climate hazard risk, and the models are generally less reliable for predicting the intensity or frequency of extreme weather events.[17] Climate science and modelling precision must "catch up" with public agencies' interest in adaptation planning before climate change considerations can be integrated into project scoping and design in a meaningful, cost-effective way.

However, more up-to-date information on Minnesota's current climate is helping to reduce the transportations system's vulnerability to climate risks. In particular, Atlas 14 is a new data source on precipitation frequency generated from rainfall-runoff models from the National Oceanic and

[16] TRB, 2013. Risk-Based Adaptation Frameworks for Climate Change Planning
[17] Interview with Andrea Hendrickson, State Hydraulic Engineer, 7/22/2015

Atmospheric Administration (NOAA) that allows for more precise flooding projections. Precipitation frequency estimates are based on data networks that are denser and cover longer periods of record than those used in the past: an average length of 50 years, which is more than double the record used in original studies. Estimates are based on new techniques for generating probability distributions, spatial interpolations, and mapping.[18] Within MnDOT, Atlas 14 estimates are used for hydraulic design on all trunk highway projects let after June 30, 2014.[19] Due to differences in statistical techniques, there is discrepancy in current precipitation depths and frequencies between the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 point estimates and climate models, which requires that predicted precipitation from climate models undergo adjustment as percentage change, and applied to Atlas 14 current precipitation depths during scenario analysis.[20]

THE IMPACT OF CLIMATE CHANGE ON STATEWIDE PLANNING

The trends in the previous section highlight climate risks and their potential impacts in Minnesota. This next section summarizes the key impacts of climate change and adaptation strategies that will affect MnDOT's asset management, capital planning, operations, and maintenance functions. These impacts and strategies are summarized in

Table 2 below, followed by a discussion of design implications, planning approaches, and existing adaptation strategies pursued by MnDOT and other transportation agencies around the country and the world

Table 2: Potential Climate Change Adaptation Strategies

Phase	Potential Climate Change Adaption Strategies
Planning & Project Selection	• Establish planned evacuation routes • Relocate infrastructure and communities at risk • Integrate climate risk hazards into asset management plans • Plan for accelerated pavement and asset degradation due to increased weathering
Project Design	• Incorporate adaptation assessments into project scoping and design selection • Adjust design life of infrastructure relative to climate hazard risks • Expand best management practices to improve drainage and stormwater storage at project sites
Project Construction	• Prepare crews for work hazards related to extreme weather
Maintenance & Operations	• Increase maintenance frequency for pavements and electrical systems • Address safety concerns for maintenance workers during extreme weather events • Plan for road closures and traffic incidents during extreme weather events • Increase culvert and bridge inspections

18 NOAA Atlas 14 Volume 8 Version 2.0
19 MnDOT Tech Memo 13-08-B-04: Use of Atlas 14 Volume 8 Precipitation Frequency Estimates (May 2013)
20 MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project

Design Implications

A barrier to considering climate change impacts in infrastructure design is the misaligned terminologies of extreme weather events used by climate scientists and design events used by engineers. Engineers refer to bridges in terms of 100-year design lives and design events (often the 2% probability storm or 50-year storm or even the 100-year storm), but climate scientists refer to a 10-year storm as an extreme weather event. Climate models additionally predict rainfall on a daily basis (sometimes reporting only monthly or annual average rainfall), which is not an appropriate timeframe for most hydraulic design.[21]

Transportation infrastructure consists of subsurface conditions, materials specifications, cross sections and standard dimensions, drainage and erosion, structure, and location engineering.[22] Approaches to changing design standards to address climate change are similar to those made to building codes to adapt to earthquakes. Research on materials, soils, and structures has informed how design can increase buildings' resilience to forces applied by seismic events.

One strategy to account for greater uncertainty in the long-term is to design infrastructure with shorter useful lives, which creates more opportunities to change the design to reflect new and more up-to-date climate data and design standards. This particular strategy is controversial, because it goes against MnDOT's asset management strategy to keep the state's assets in service for as long as possible.[23] In the short-term, building infrastructure with shorter design lives may cost less, though installation costs will likely maintain high prices. However, if environmental conditions do not change as much as expected in the long-term, infrastructure must be re-built more frequently and costing more overall.[24] There is need for engineering design standards to reflect increased water stress and other environmental factors in the short-term, and in the long-term, increased temperatures, temperature ranges, and wind load. "Smart" technologies may enable infrastructure to change flexibly, according to environmental conditions.

EXISTING INITIATIVES

Minnesota

- *Bridge Scour Plan of Action:* Bridge scouring occurs when quickly moving water and runoff removes sediment from the abutments and piers of a bridge, compromising its structural integrity. MnDOT is addressing bridge scouring through a monitoring webpage and a Bridge Scour Plan of Action for bridges identified as scour critical, developing a Bridge Office Flood Response Plan, and setting up a cooperative agreement with USGS to monitor flood scour.
- *Bond-funded projects:* MnDOT dedicated $50 million to mitigation projects on flood-prone highways. Construction on these projects is expected to terminate by the 2016 fiscal year.
- *Support up-to-date research projects:* MnDOT established a cooperative agreement with USGS to fund crest gages for data collection on hydrology, and to assist with outreach on Atlas 14, a new data source on precipitation frequency from the National Oceanic and Atmospheric Administration
- *Fund new research projects:* including ditch or swale infiltration to reduce runoff, roadway overtopping protection, scour monitoring implementation, and other strategies to mitigate the harmful effects of extreme weather events on transportation assets.
- *Interagency Collaboration:* The Interagency Climate Adaptation Team (ICAT) was developed in 2009 to facilitate collaboration between state agencies on climate change adaptation efforts. MnDOT, the state departments of health, agriculture, natural resources, commerce, public safety, as well as the Pollution Control Agency and the Metropolitan Council, have all contributed to a report on opportunities for interagency and collaborative action in climate adaptation.[25] Additionally, MnDOT was involved with the Climate Solutions and Economic Opportunities project to address climate change mitigation. This effort provides stakeholders with opportunities to collaborate in taking short-term actions to reduce greenhouse gas emissions.

[21] Interview with Andrea Hendrickson, MnDOT Hydraulics Engineer.
[22] Myeyer (2009).
[23] MnDOT, 2014. Transportation Asset Management Plan (Draft). Chapter 6: Life Cycle Cost Considerations.
[24] Meyer, Design Standards for the U.S. Transportation Infrastructure: Implications of Climate Change, September, 2006.
[25] Adapting to Climate Change in Minnesota: 2013 Report of the Interagency Climate Adaptation Team

FLASH FLOOD VULNERABILITY AND ADAPTATION ASSESSMENT PILOT PROJECT

As part of one of 19 pilot studies across the country sponsored by FHWA to examine the effects of climate hazards on transportation systems, MnDOT conducted a system-wide assessment of the trunk highway network's vulnerability to increased heavy precipitation in districts 1 and 6. The project team scored and ranked 316 bridges, 521 large culverts, 920 pipes and approximately 45 miles of road segments paralleling streams based on their sensitivity and exposure to heavy precipitation as well as the system's adaptive capacity. The project also included an adaptation analysis of two culverts: one on MN 61 over Silver Creek in district 1 and a culvert on US 63 in the city of Spring Valley in district 6. The analysis evaluated the current performance of each culvert as well as three adaptation options. All options were assessed against three future climate scenarios and a preferred option was identified based on lowest lifecycle cost analysis, including direct repair and replacement costs as well as detour and safety costs.

Figure 5: Asset vulnerability to flash flood events in MnDOT District 1

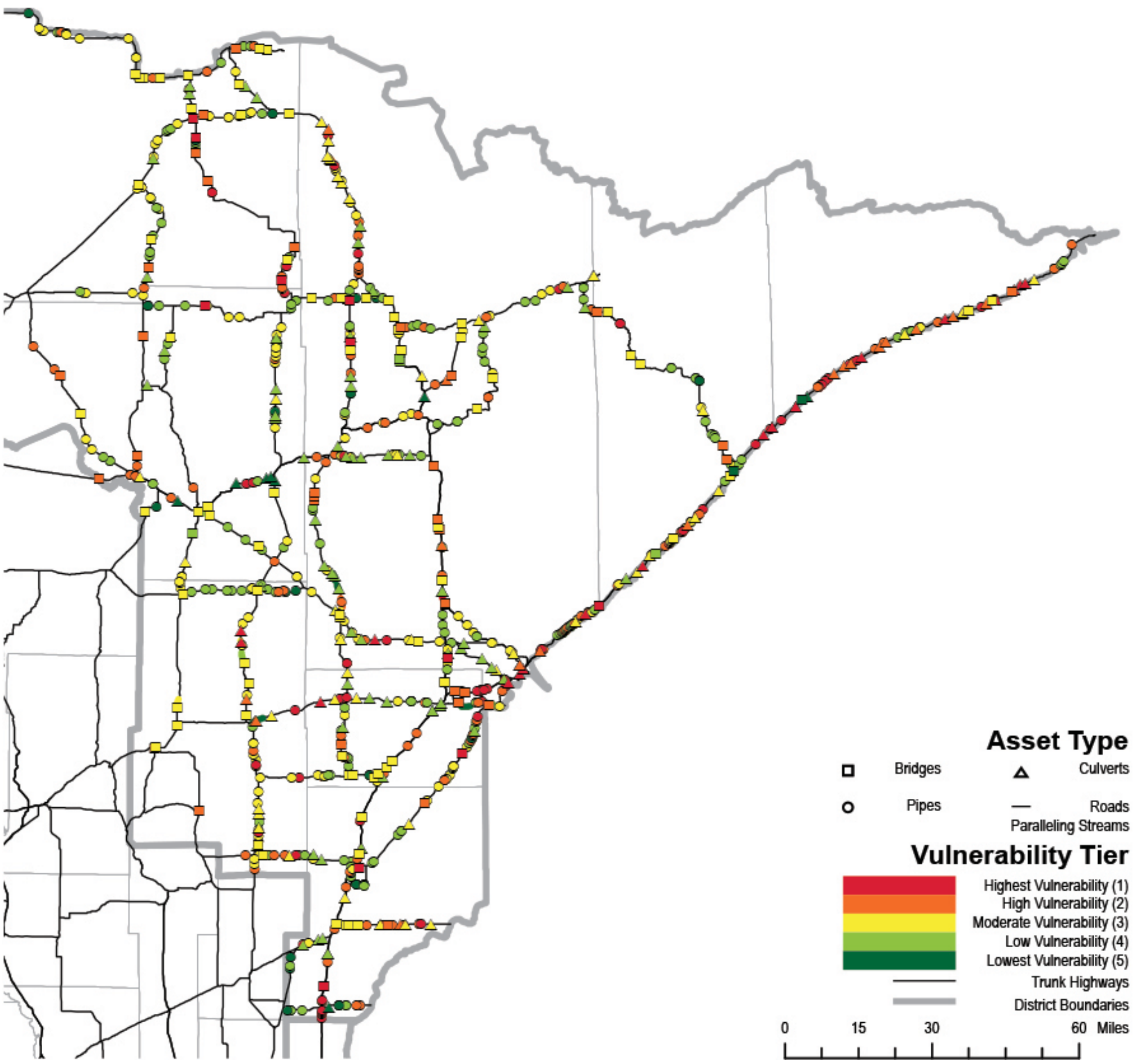
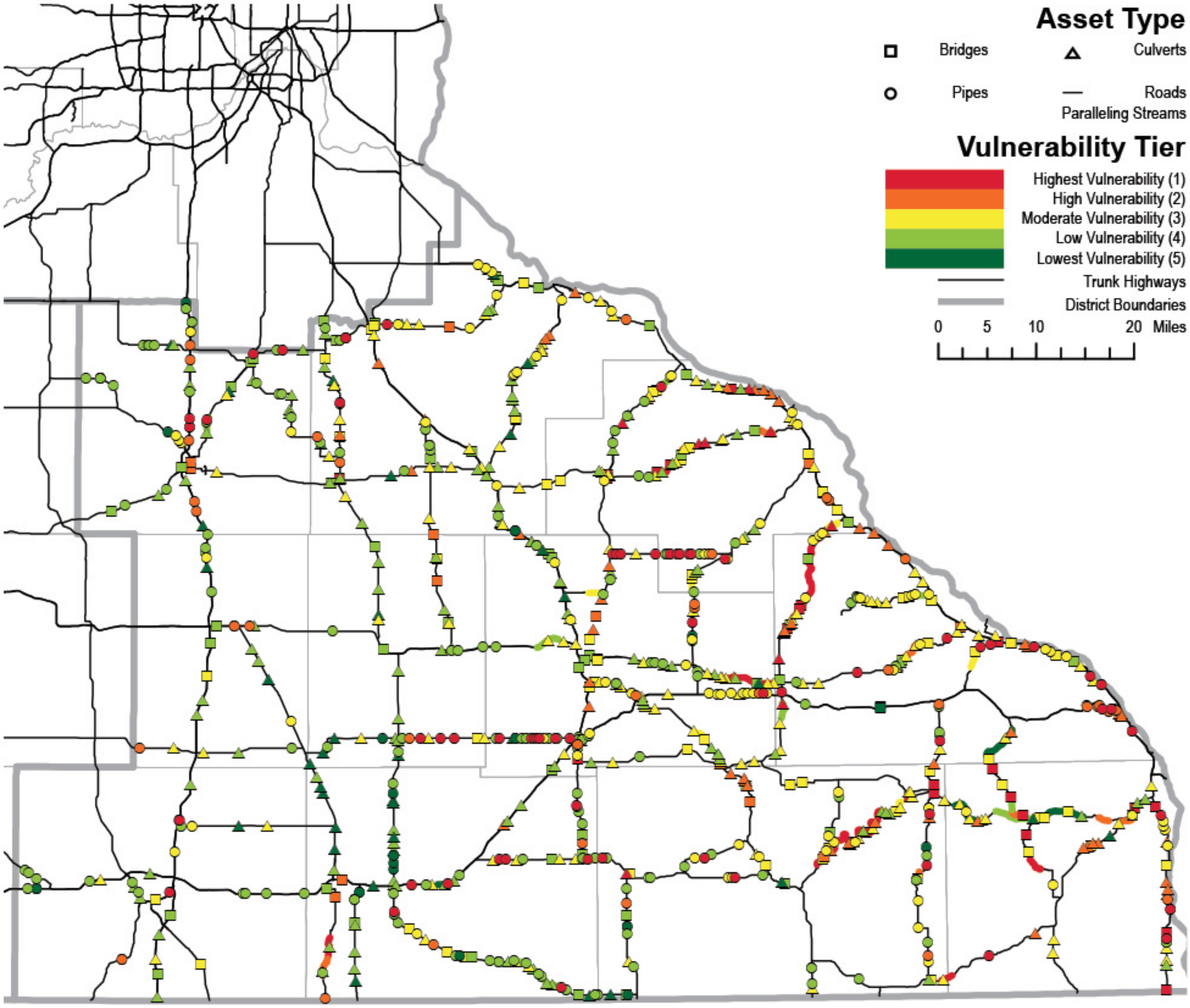


Figure 6: Asset vulnerability to flash flood events in MnDOT District 6



Other States

MnDOT and its transportation partners can look to other states for examples of how transportation agencies are addressing climate change through their own work. A few noteworthy examples from peer agencies follow.

VERMONT: RIVER SCIENCE TRAINING

The Vermont Agency of Transportation (VTrans) developed a River Science Climate Resilience Strategy in partnership with the state Agency of Natural Resources, which requires river science training for certain engineering and operations staff, and helped VTrans to modify its hydraulics manual and roadway slope designs to account for river movements and soil erosion. VTrans went on to retrofit roads and bridges to increase their resilience to flooding, which also addressed pollutant runoff concerns for the state's lakes and streams. This effort won a 2015 Environmental Excellence Award from the Federal Highway Administration.[26]

[26] Climate Change Adaptation and Resilience: River Science Climate Resilience Strategy

NEW MEXICO: INTEGRATE LAND USE AND TRANSPORTATION PLANNING WITH CLIMATE CHANGE

Land use systems that are less dependent on private car travel are more resilient to climate change, because the infrastructure needs for accommodating a population in single-occupancy vehicle is much greater than other travel modes. The Central New Mexico Climate Change Scenario Planning Project (July 2013 - Spring 2015) used scenario planning to develop a strategy for the Albuquerque region to reduce future greenhouse gas emissions and prepare for climate change impacts. The scenarios informed development of the state's long-range transportation plan, as well as related planning efforts at the state, local, and federal level.[27] The project demonstrated to stakeholders that certain patterns of development are more resilient to climate impacts than others, highlighting the important feedbacks between land development and transportation systems.

ALASKA: PERMAFROST PROTECTION AND EVACUATION ROUTES

Because of its coastal exposure, high latitude, extensive permafrost coverage, large geographic area, indigenous populations reliant on current ecosystem balance, and varied topography, Alaska is arguably the state facing the highest degree of climate risk, and experiencing the effects of climate change first. The State's Department of Transportation and Public facilities is pursuing adaptation efforts such as permafrost protection, drainage improvements, flood mitigation, and development of evacuation routes and shelters. For evacuation routes, the FHWA provided funding to raise elevation of existing roads above flood levels, and to extend an evacuation road.[28]

WASHINGTON STATE: "MAINSTREAMING" CLIMATE ADAPTATION INTO NEPA/SEPA REVIEW

Washington state's Department of Transportation (WSDOT) Environmental Stewardship Office developed guidance in 2009 for undertaking project-level climate change evaluations, and became the first DOT in the nation to incorporate climate change and greenhouse gas emissions into cumulative effects analysis mandated under national and state Environmental Policy Acts (NEPA and SEPA)[29].The guidance is based on climate information generated from the *Washington Climate Change Impacts Assessment* and a statewide vulnerability assessment of WSDOT's assets. The guidance provides a standard qualitative language template on cumulative effects, and requires project teams to document climate threats in the project area, and document how the project will be designed to be resilient or resistant to climate threats.

International

The Federal Highway Administration (FHWA) conducted a review of transportation agencies in the U.K, New Zealand, Australia, Denmark, Norway, the Netherlands, Canada, and Korea, with regards to how they are addressing climate adaptation through frameworks, strategies, measures, risk assessments, long range planning and land use, changes in design standards, maintenance and operations, asset management, and research.[30] These agencies face common challenges: uncertainties of the impacts and timeframes of future climate variability and greenhouse gas emissions, as well as adaptation needs that exceed current funding availability. They recognize that it is often more cost-effective to "climate proof" infrastructure during the construction phase, rather than to adapt infrastructure once it is in operation, and thus seek to focus on adaptation planning during the scoping phase of new infrastructure projects. Adaptation considerations are most commonly integrated into planning and design of infrastructure that interfaces directly with hydrological systems, including drainage systems, bridges, and culverts. While agencies recognize the potential impacts of climate change on maintenance and operations, few are making changes to these activities at this time: adaptation is focused on infrastructure planning and design.

[27] Central New Mexico Climate Change Scenario Planning Project
[28] Alaska Department of Transportation and Public Facilities, 2009. Climate Change in Alaska: Transportation Infrastructure and Climate Change.
[29] Washington State Department of Transportation, 2014. Guidance for NEPA and SEPA Project-Level Climate Change Evaluations.
[30] FHWA (January 2015) International Practices on Climate Adaptation in Transportation: Findings from a Virtual Review