MICHIGAN DOT CLIMATE VULNERABILITY ASSESSMENT PILOT PROJECT

Final Report

prepared for

Federal Highway Administration

prepared by

Michigan DOT &

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with

Stratus Consulting

U.S. Department of Transportation
Federal Highway Administration

MDOT
Michigan Department of Transportation

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- Michigan Department of Community Health;
- Michigan Environmental Council;
- Michigan Department of Natural Resources;
- Great Lakes Integrated Sciences + Assessments Center;
- University of Michigan;
- Michigan Infrastructure Transportation Association;
- Southwest Michigan Planning Commission;
- Wexford County Road Commission;
- MDOT Transportation Asset Management Council;
- Michigan State Police Emergency Management and Homeland Security Division; and
- Federal Highway Administration, Michigan Division.

MDOT Working Group:

- Bureau of Planning
- Bureau of Highway Development
- Bureau of Field Services.

Consultant Team:

- Cambridge Systematics, Inc.; and
- Stratus Consulting.

EXECUTIVE SUMMARY

Project Overview

This study was conducted by the Michigan Department of Transportation (MDOT) to better understand future climate and extreme weather risks, and to identify approaches for integrating climate risk analysis into MDOT's planning practices. This work included:

- Identifying the primary climate stressors impacting the transportation system in Michigan;
- Reviewing the transportation and climate data needed to assess those impacts and identifying gaps that limit what can be done with current data;
- Examining risks from future climate and extreme weather impacts;
- Assessing the vulnerability of transportation assets to those risks; and
- Defining strategies for incorporating this information into asset management and agency decision-making.

This study is one of 19 national Pilot projects funded by the Federal Highway Administration's (FHWA) climate change vulnerability assessment program, and has been guided by the FHWA's *Climate Change and Extreme Weather Vulnerability Assessment Framework.* A Technical Advisory Committee and an internal MDOT Advisory Group were convened throughout the course of the study to review products and coordinate on future opportunities to address climate change and extreme weather impacts in MDOT and partner agency processes.

The scope of this study was on the Michigan highway system owned and operated by MDOT. It provides a foundation to help evaluate the adequacy of planning, design guidelines and standards, and operation and maintenance practices that may be impacted by future climate conditions. Due to the statewide scale of this analysis, the study focused on a small number of assets, but identified opportunities to collaborate with local planning efforts that include a broader range of asset owners and types.

Climate Analysis

Michigan faces a unique set of climate change challenges, compared to coastal regions. Extreme precipitation events in recent years have caused increased erosion, bridge scour, and localized flooding issues that present management and operational challenges to Michigan's transportation system. Building on recent experience, MDOT examined two major climate stressors – precipitation and extreme heat – considering annual averages, seasonal variation, and the frequency of extreme weather events (e.g., the amount of precipitation in the 100 year storm, the number of days over 95 °F). For instance, warmer winters with reduced snowfall, but increased rain pose somewhat different operations and maintenance challenges for safe, passable roadways. Similarly, increased temperature variability in the winter months could increase the frequency of freeze/thaw cycles in some parts of the State, accelerating the deterioration of Michigan's roads. Key asset management issues of concern to both immediate and long-term operations and maintenance issues associated with these two primary climate stressors, precipitation and temperature, are identified in Section 2.

MDOT used two emissions scenarios from the Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment. For each scenario, five climate models were selected that represent a range of future climate impacts. While all of the models show increased temperature and precipitation, they ranged from relatively drier and cooler to relatively warmer and wetter. Using a range of models helped to address the inherent uncertainty of future climate impacts. These models were used to generate average annual, seasonal, and extreme event projections for two emissions scenarios and two future time periods: 2050 and 2100.

Climate Analysis Findings

Relevant general findings for Michigan for precipitation, extreme precipitation and temperature, included:

- Average annual precipitation is expected to increase across Michigan, especially in the winter, but the *amount* of increase is expected to vary by scenario and region of the state. The scenarios with the highest level of emissions show an increase in the 100 year storm event of as much as 3-inches by 2100, almost double the current state average of 4 inches.

- Average annual temperatures in Michigan are projected to increase, with winter temperatures expected to increase faster. Increasing winter temperatures means fewer days below freezing and fewer freeze-thaw days than are experienced today. The climate models show the Upper Peninsula holding steady in the number of freeze-thaw days by 2050 (ranging from 6 percent fewer to 4 percent more), but the general trend is for many fewer freeze-thaw days. By 2100, the Upper Peninsula is expected to decline by 12 to 33 percent, the northern part of the Lower Peninsula is expected to decline by 19 to 40 percent and the southern Michigan declining by 25 to 50 percent.

- The combination of increased winter temperatures and precipitation indicates that Michigan will experience more rain and less snow in the future, especially under the higher emissions scenario. These changes will impact how MDOT conducts operations across the State.

- The number of annual days over 95°F is expected to increase, but is not expected to increase dramatically until after 2050. Michigan has an average of 1 to 2 days over 95 °F currently. By

2100, the models show an increase to between 5 to 20 days in the lower emissions scenario and as much as 60 days in the higher emissions scenario.

Assessment Process and Results

The climate analysis findings were used to assess the criticality, vulnerability, and risk for all MDOT-owned bridges, trunk line roadways, pumps, and culverts. Determination of asset criticality focused on the consequences of removing an asset from service, building off of work MDOT had done to evaluate the criticality of scour critical bridges.

Vulnerability is typically was assessed using three factors – exposure (increase in extreme weather), sensitivity (ability to withstand that increase) and adaptive capacity (ability of the system to absorb impacts). At the statewide scale, data limitations meant that the analysis focused primarily on exposure to climate stressors. Exposure was determined by intersecting transportation asset data with projected changes in the precipitation and temperature. These results were multiplied by the vulnerability and criticality scores to generate a risk score for each asset. The results of the statewide risk assessment reveal several notable trends:

- Most of the highest-risk assets were located in the southern portions of the State, in part due to the greater volume of travel on these assets;
- For extreme precipitation, the highest-risk roadways were generally found in and around the major metropolitan areas in the southern third of the Lower Peninsula; and
- Roadways with the highest risk scores for extreme heat are generally found in the Detroit area, which is a function of both the relatively high vulnerability scores in this area (due to urban heat island effects), as well as the high criticality of these roadways.

A focused risk analysis was performed for five areas across the state to illustrate the exposure of specific assets to risk and to better capture the sensitivity of those assets to climate stressors and adaptive capacity of the system. In general, these analyses revealed that additional data on elevation, flood plains, and land use would be helpful to provide a more robust assessment of asset vulnerability. Detail on these focus areas are provided in Section 4.

Next Steps

The study recommends opportunity areas for integrating vulnerability assessment findings into MDOT asset management processes, including;

- State Long Range Planning (including monitoring and capacity building, integration into the State Long Range Plan, and corridor planning);

- Design & Construction (including climate-sensitive pavement materials analysis); and
- Operations & Maintenance.

Specific action items include;

- Collect and data that support a complete analysis of vulnerability for specific assets, including data on flood plains, elevation, and land use. While these data are generally useful, a more focused analysis of specific assets is likely to yield more actionable information for MDOT as it considers investment choices on key state-owned roads.
- Defining climate resiliency goals and incorporate those goals into MDOT's long range plan update.
- Coordinate with partner agencies to identify high-risk areas in the State and begin monitoring roadway closure frequency and duration in these areas.
- Evaluate the economic impacts of roadway closures in various parts of the state (potentially on the corridors defined above) and establish thresholds for acceptable closure levels for various precipitation scenarios.

The complete list of action items specific to each of the opportunity areas, as well as a summary of the lessons learned throughout the course of this study, are presented in Section 5.

1.0 PROJECT OVERVIEW

This Michigan Department of Transportation (MDOT) conducted this assessment to better understand future climate and extreme weather risks and to identify approaches for integrating climate risk analysis into MDOT's planning practices. This work included:

- Identifying the primary climate stressors impacting the transportation system in Michigan;
- Reviewing the transportation and climate data needed to assess those impacts and identify gaps that limit what can be done with current data;
- Examining risks from future climate and extreme weather impacts;
- Assessing the vulnerability of transportation assets to those risks; and
- Defining strategies for incorporating this information into asset management and agency decision-making.

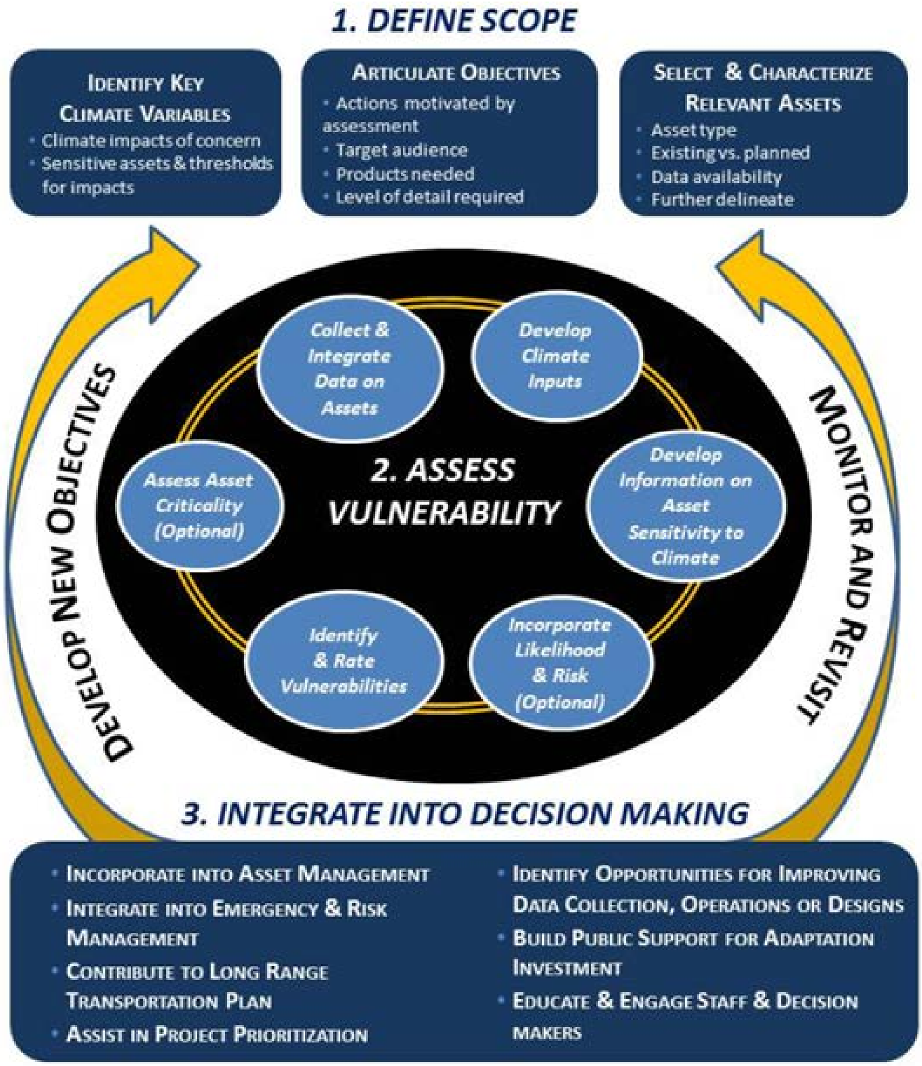
Approaching a climate-based vulnerability assessment through the lens of asset management and building around MDOT's existing asset management databases will help MDOT better manage climate-related risks and protect the investment made by the citizens of Michigan in transportation infrastructure.

1.1 FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework

This study is one of 19 national Pilot projects funded by the Federal Highway Administration's (FHWA) climate change vulnerability assessment program. The study effort has been guided by the FHWA's *Climate Change and Extreme Weather Vulnerability Assessment Framework* (the "framework"). The basic components of the framework include:

1. Define objectives and scope;
2. Assess vulnerability; and
3. Integrate vulnerability into decision-making.

Figure 1.1 FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework



In 2010, FHWA funded State Departments of Transportation (DOT) and Metropolitan Planning Organizations (MPOs) to pilot an earlier version of the framework described above through a series of vulnerability and risk assessments of infrastructure to the projected impacts of global climate change. Five pilots were conducted in coastal States across the country as part of this effort.

Building upon the lessons learned from the initial pilot studies, a second round of pilots were initiated in 2013 to further test approaches to conducting vulnerability assessments under the amended framework for transportation infrastructure and to analyze options for adapting and improving resiliency. Michigan was one of several pilot studies that expanded the reach of FHWA's conceptual framework to inland areas.

1.2 Study Approach

Michigan faces a unique set of climate change challenges, as compared to coastal regions. This assessment is focused on developing a better understanding of risk associated with potential climate impacts unique to Michigan from two primary climate stressors: precipitation and extreme heat. Impacts to MDOT roadways and bridges (including drainage infrastructure) are the primary focus of the analysis. This assessment also provides a foundation to better evaluate the adequacy of design guidelines, standards, and operation and maintenance practices that may need to be adapted due to future climate conditions. To achieve these objectives, the following steps were taken:

- Assembled a technical advisory committee and internal working group to help to guide the process;
- Collected asset and geospatial data from MDOT and other partners;
- Identified and analyzed climate stressors of concern to MDOT;
- Conducted a risk assessment of MDOT assets based on criticality and vulnerability of MDOT bridges, roadways and drainage infrastructure (including culverts and pumps); and
- Developed recommendations for integrating risk analysis findings into asset management programs, including opportunities for corridor planning.

The study team consisted of the MDOT Project Manager, FHWA Michigan Division Transportation Planner and the consultant team. MDOT provided the study team with asset datasets for the vulnerability assessment, who then conducted a gap analysis to identify missing data elements. The gap analysis focused on information needed to assess climate risk, such as location, elevation, drainage, condition, and age of infrastructure. The study team also conducted a criticality assessment to narrow the number of assets for in-depth evaluation, and to provide inputs into the risk assessment. The methodology the study team developed to conduct this criticality assessment was informed by the MDOT scour critical bridge inventory and is addressed in detail in Section 3 of this report.

The study team developed spatial climate stressor data using several General Circulation Models (GCM) that were localized (spatially disaggregated from the large cells used by these models into more fine grained data based on observed climate data from sets of weather stations in Michigan). These data were then integrated into a Geographic Information System (GIS) framework to support an intersection analysis of MDOT asset information and climate data. Additional data sets, such as floodplain and elevation information, where available, were integrated with the analysis. The study team identified high, medium, and low thresholds (based on a continuous scale) where climate stressors could affect MDOT transportation assets. The development of criticality and vulnerability scores, based on these thresholds and other weighted factors, lead to an overall risk score for each asset or asset type in a specific area. Detailed information on these findings can be found in Section 4 of this report.

Technical Advisory Committee

The study team identified and convened a Technical Advisory Committee (TAC) to provide insight to the process and to help share data resources as appropriate. Members included representatives from various state agencies, advocacy groups, academic institutions, and local planning partners.

The study team convened three meetings with the TAC throughout the course of the study. These meetings were designed to;

- React to the work plan and identify potential linkages to other climate-related efforts in Michigan;
- Reflect on the gap analysis and refine the risk analysis approach; and
- Discuss findings from the vulnerability assessment and opportunities to integrate the approach into MDOT's asset management decision-making processes.

During the final meeting of the TAC the study team presented findings from the risk and vulnerability assessments at both a statewide and more focused scale to better understand the application, and limitations, of the study effort. Further discussion of the focused risk assessment can be found in Section 3.

TAC Affiliations

- *GLISA*
- *Michigan Infrastructure Transportation Association*
- *Southwest Michigan Planning Commission*
- *Wexford County Road Commission*
- *Southwest Michigan Planning Commission*
- *MDOT/Transportation Asset Management Council*
- *Michigan State Police Emergency Management & Homeland Security Division*
- *FHWA Michigan Division*
- *Michigan Department of Community Health*
- *MDNR – Forest Resources*
- *Michigan Environmental Council*

MDOT Working Group

In addition to the TIC, an internal MDOT working group consisting of members from the Planning, Highway Development, and Field Services divisions was convened with experience across asset types (pavement, bridge, culverts, pumps) and functions (planning, design, construction, operations). The MDOT working group's objective was to respond to the analysis methods being developed by the study team and to provide recommendations for incorporating the findings into MDOT's planning processes. This group also provided the base data and subsequent supplemental data necessary to support the analysis. This working group was convened on several occasions throughout the course of the study.

Study Scope

MDOT selected the highway system they own and operate for the scope of this study, including:

- Pavement
- Bridges
- Culverts
- Drainage infrastructure (pumps and storm sewers).

While this was the focus, the study team did pay attention to other infrastructure, in particular local road infrastructure and other modes, where possible. Due to the statewide scale of this analysis, it was important to maintain a focus on as limited a number of assets as possible. Future opportunities for integrating with local planning efforts that include a broader range of asset owners and types are discussed in the recommendations in Section 4.

Data Collection, Gaps, and Analysis

Data was collected from MDOT, downloaded from Michigan's Geographic Data Library (MGDL), various project partners, and the Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD) 2013. A gap analysis was performed to identify where additional data elements may be needed. The gap analysis is available as Appendix A. The quality of the asset data was very good for analysis purposes. However, the study team's approach to overlay climate stressor data with asset data was complicated by incomplete floodplain data and low resolution elevation data. The ability to draw conclusions from a geospatial analysis with these data limitations, and recommendations for overcoming these types of data challenges, are addressed in the Lessons Learned section of the report (Section 5).

2.0 CLIMATE ANALYSIS

2.1 Key Issues of Concern

The study team and the MDOT working group began the climate discussion by identifying climate variables of interest to MDOT based on the impact of recent extreme weather events on the transportation system. Key issues of concern to both immediate and long-term operations and maintenance included:

- Increased erosion from intense precipitation;
- Seasonal precipitation changes – both amount and type (snow vs. rain);
- Bridge scour;
- Freeze/thaw;
- Great Lakes ice cover (and impact on lake effect snow) and lake levels;
- Road buckling; and
- Wildfire, especially in the Upper Peninsula and northern Lower Peninsula.

Extreme precipitation events have occurred in recent years, leading to increased erosion, bridge scour, and localized flooding issues. Specific interest in future frequency of extreme precipitation events over a short duration (i.e., three to six inches in a 24-hour period) was identified as a particular concern, though MDOT staff recognized the challenges with forecasting precipitation at a fine grained level. In addition to extreme precipitation events, seasonal changes in precipitation also were identified as a concern. Among other asset management challenges, the combination of increased precipitation in winter months and decreased precipitation in summer months creates optimal conditions for increased wildfire risk.

Increased winter temperatures and greater temperature variability also were identified as a concern. Warmer winters could result in decreased snowfall and increased rain, which pose different operations and maintenance challenges for safe, passable roadways. Increased temperature variability in the winter months may increase the frequency of freeze/thaw cycles, accelerating the deterioration of Michigan's roads.

Another concern raised was the impacts of anticipated annual and seasonal shifts in both temperature and precipitation on the Great Lakes. Warming temperatures could result in reduced ice cover and more open water, which could lead to more lake effect storms. Drier conditions, resulting in low water levels, may impact recreation and freight movements (the

Upper Peninsula is an important source for aggregate used in roadway construction). Given the variety of factors that influence lake levels and the broader microclimate they inspire, climate models are not well suited to project impacts to the Great Lakes under different climate scenarios. This assessment drew on a large body of research on Great Lakes water levels to help inform Michigan about potential impacts.

2.2 Climate Analysis

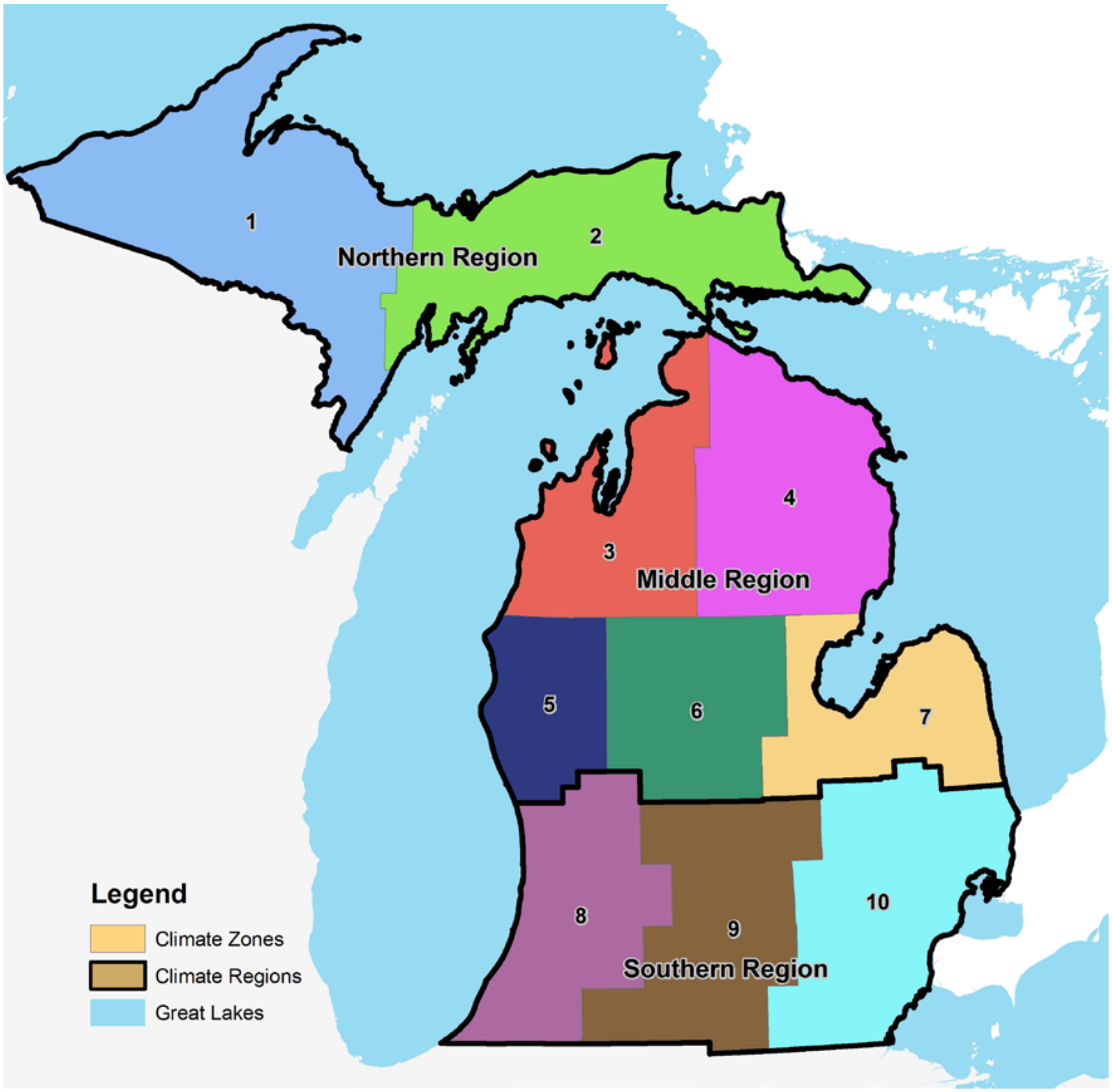
Based on the issues of concern, MDOT identified temperature and precipitation as the key climate stressors for evaluation in this study. These stressors were refined into specific climate variables for analysis, as represented in Table 2.1.

Table 2.1 Climate Variables to Examine

Issue(s) of Concern	Operationalized Climate Variables	Climate Variable for Analysis
Increased erosion from intense precipitation, decreased snow/increased rain (specific interest in extreme precipitation events in a short time period), bridge scour	• Change in 24-hour rain event (30-year, 50-year, 100-year events) • Change in precipitation as snow versus rain	Extreme precipitation
Freeze/thaw Great Lakes ice cover (and impact on lake effect snow)	• Average annual number of days below freezing (change from present) • Number of consecutive frost-free days (change from present)	Winter temperatures/ temperature variability
Pavement deformation and thermal expansion	• Average annual number of days over 95 degrees	Extreme summer temperatures

Temperature and precipitation data were generated for the 10 climate regions in Michigan, as defined by the Great Lakes Integrated Science and Assessment (GLISA) at the University of Michigan. For this report, most analyses are summarized into three broader regions (Figure 2.1): the Northern region encompasses the Upper Peninsula, the Middle region encompasses the northern portion of the Lower Peninsula, and the Southern region encompasses the southern portion of the Lower Peninsula and the State's three largest urbanized areas. This allowed for a more focused and manageable approach to understanding the range of possible climate futures across the State, and the potential impacts to MDOT transportation assets. It also helped to capture much of the variation in current and expected future weather patterns across the State.

Figure 2.1 Michigan Climate Regions and Groupings



Emission Scenarios and Climate Sensitivity

The Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment concept of Representative Concentration Pathways (RCP) was used in the assessment. The four RCPs capture the extent to which greenhouse gas emissions from human activity continue as they have, accelerate, or decline. They were developed by IPCC based on an extensive literature review. The RCPs are defined by an expected level of radiative forcing – the extra heat the lower atmosphere will retain as a result of additional greenhouse gases, measured in Watts per square meter (W/m^2). Additional information about the four RCPs used in the IPCC's 5th assessment can be found in the Climate Analysis memo in Appendix B.

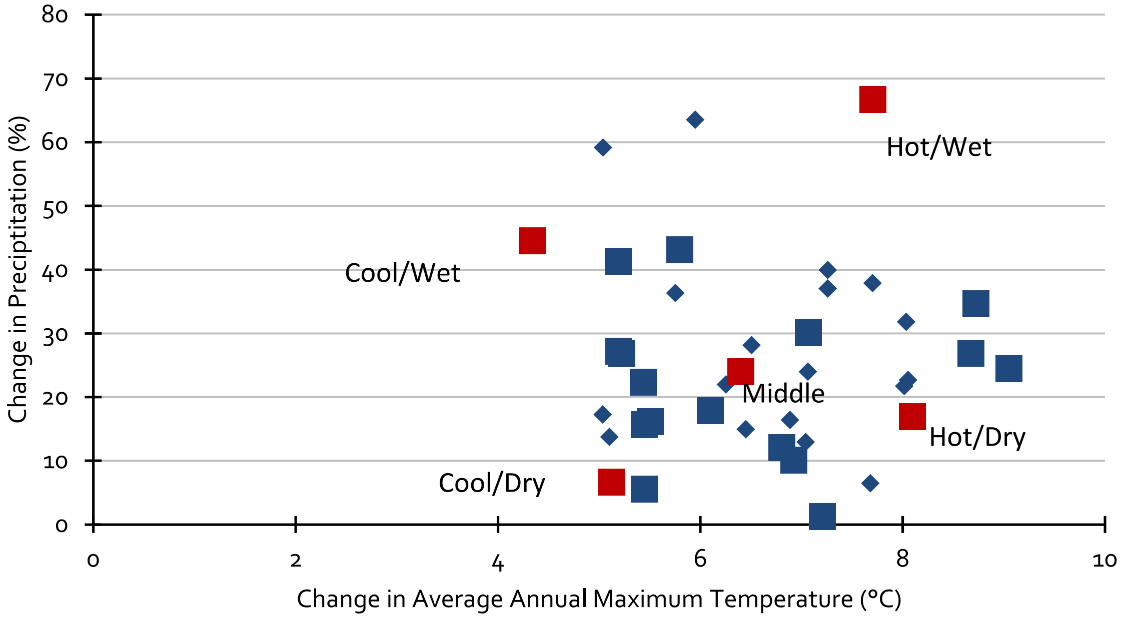
We used two of the RCPs to consider a range of potential future impacts. While there is no consensus on which scenario is most likely, we used RCP 6 (hereafter medium emissions scenario) and RCP 8.5 (hereafter high emissions scenario), because they are most consistent with recent global trends in greenhouse gas emissions. The medium and high scenarios were chosen because these levels of emissions appear likely without significant changes in behavior, and the advisory committee found that these two scenarios best helped MDOT characterize risk in a way that would be constructive to MDOT.

General Circulation Models

General Circulation Models (GCM) are used to project changes in global climate at a coarse scale (often 150 – 300 km cells covering the entire earth). These models capture the interaction among the atmosphere, oceans, land surface, and ice over the entire Earth to project climate variables, including temperature, precipitation, and winds for each cell. Climate models are developed by universities and governmental research laboratories across the globe but are coordinated through the Coupled Model Intercomparison Project (CMIP) to provide some standardization of protocols. We used output from the IPCC's latest report corresponding to the CMIP5 set of models in the analysis.

Figure 2.2 shows change in average annual maximum temperature (^{o}C) and precipitation (percent) by climate model for Michigan under the high-emissions scenario in 2100. Each dot represents a climate model projection. The squares (red and blue) are the subset of models that can estimate extreme weather events (a critical factor for this study). The red squares are the five climate models selected for this study, representing the range of models from drier and cooler to warmer and wetter.

Figure 2.2 Change in Temperature and Precipitation by Climate Model



These climate models were used to generate average annual, seasonal, and extreme event projections for two emissions scenarios (medium and high, as described above) and two future time periods. The future time periods represent the average climate of a 20-year period centered around 2050 (2041 to 2060) and 2100 (2091 to 2110). A 20 year period is used because of natural variation in climate from year to year. The result of the analysis is 20 total outputs for each climate stressor (5 models X 2 periods X 2 emissions scenarios).

Further detail on the climate analysis, including the process and the method for identifying extreme event projections, is available in Appendix B.

Qualitative Analysis

The study team conducted a literature review to capture recent trends in lake levels and gain a better understanding of potential future conditions in two areas that could not readily be captured with the climate models – lake levels and wildfire conditions.

Lake Levels

Climate has a dominant influence on water levels in the Great Lakes; however, most climate models estimates of water bodies are based on data from ocean, making them a poor fit for smaller fresh water bodies. Changes in lake levels are also complex, fluctuating from year to year, making them challenging to predict.

The water balance in the Great Lakes varies both seasonally and on a year to year basis (Lenters et al., 2013). Seasonally, the highest precipitation tends to occur in the summer months, whereas the highest rates of evaporation occurs between November and March, driven by a large temperature differential among the warmer water and cold air, low-relative humidity, and high-wind speeds (Lenters, 2004).). Approximately 70 percent to 90 percent of the annual evaporation from Lake Superior occurs in these winter months (Blanken et al., 2011).

Another complicating factor in the lake levels is the role of ice cover. Annual ice cover is highly variable, but records suggest that it is decreasing. The annual maximum ice coverage in recent years, which averaged 43 percent from 2003 to 2013, is lower than the 1962 to 2013 average of 52 percent (Pryor et al., 2014). Despite these decreases, ice cover varies dramatically from year-to-year. For example, in the unusually cold winter of 2014, the maximum extent of ice cover was 92 percent (NOAA, 2014). However, in 2012, the maximum ice coverage was only 13 percent, one of the lowest years on record (NOAA, 2014). These changes in ice coverage influence the Great Lakes water budget and contribute to annual variability. Reduced ice coverage can result in further increases in water temperatures and evaporation (Austin and Coleman, 2007).

On an hourly to daily timescale, short-term fluctuations in water levels are caused by winds and changes in barometric pressure. On a seasonal basis, snowmelt and spring rainfall cause higher water levels in the spring and early summer. Finally, long-term fluctuations occur based on low or high water supply conditions driven by climate patterns. Lakes Superior, Michigan, Huron, and Erie have experienced lower-than-average annual water levels in recent years (Gronewold et al., 2013).

Wildfire

In Michigan, the fire season extends from spring through fall (Michigan State University, 2014). Michigan's busiest fire season is in the spring, when dead leaves and grass from the previous season provide fuel and windy, dry days create an environment that encourages fires to ignite and spread (MDNR, 2014; Michigan State University, 2014).

Extensive research has demonstrated that climate and weather, fuels, and ignition agents are key controlling factors for forest fires (Flannigan et al., 2009; Price and Rind, 1994). Increases in air temperature are expected to influence fire in several ways, including increasing the occurrence of lightning, fuel quantity and condition (Flannigan et al., 2009), and the length of the fire season ((Price and Rind, 1994; Westerling et al., 2006). Research on historical fires in the Upper Peninsula of Michigan indicates that larger fires were associated with drier climactic conditions and droughts (Drobyshev et al., 2012). An increase in precipitation is unlikely to mitigate the effect of increasing air temperatures because warmer air increases evaporation and can hold more moisture (Flannigan and Harrington, 1988; Flannigan and Van Wagner, 1991; Flannigan et al., 2005). Parisien et al. (2011) showed that the area a fire burns tends to increase with higher temperatures, even when precipitation is high. The timing of precipitation also is important. More precipitation in the previous season actually increases wildfire risk by increasing the availability of fuel to be burned (Westerling et al., 2006; Swetnam and Betancourt, 1998; Meyn et al., 2007).

2.3 Climate Analysis Findings

Precipitation

The average annual precipitation in Michigan has been increasing in recent years, on the order of 0.45 inches per decade (based on data from 1960 to 2010; National Climatic Data Center, 2014). The increase has been similar in summer (June, July, and August), 0.12 inches per decade, and winter (December, January, and February), 0.13 inches per decade.

The vast majority of climate models project an increase in average annual precipitation in Michigan, although a small number project virtually no change, or even a slight decrease (Figure 2.3).[1] On a percentage basis, the projected average annual change is similar across all three regions. Similarly, there is considerable variability in the projections of summer and winter precipitation (Figure 2.4 and Figure 2.5). However, on average the five selected climate models project smaller increases in summer precipitation and greater increases in winter precipitation than the annual values. Notably, there is great uncertainty in the 2100 high emissions forecasts, as demonstrated by the greater range of findings from the five climate models examined.

In the figures below, the triangle represents the average change of all five models, and the horizontal bars represent the maximum and minimum values from the 5 models.

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[1] Note that the models selected illustrate a range of temperature and precipitation; however, none of the models selected for the summary showed a decrease in precipitation.

Figure 2.3 Percent Change in Average Precipitation by Scenario, Region, and Year

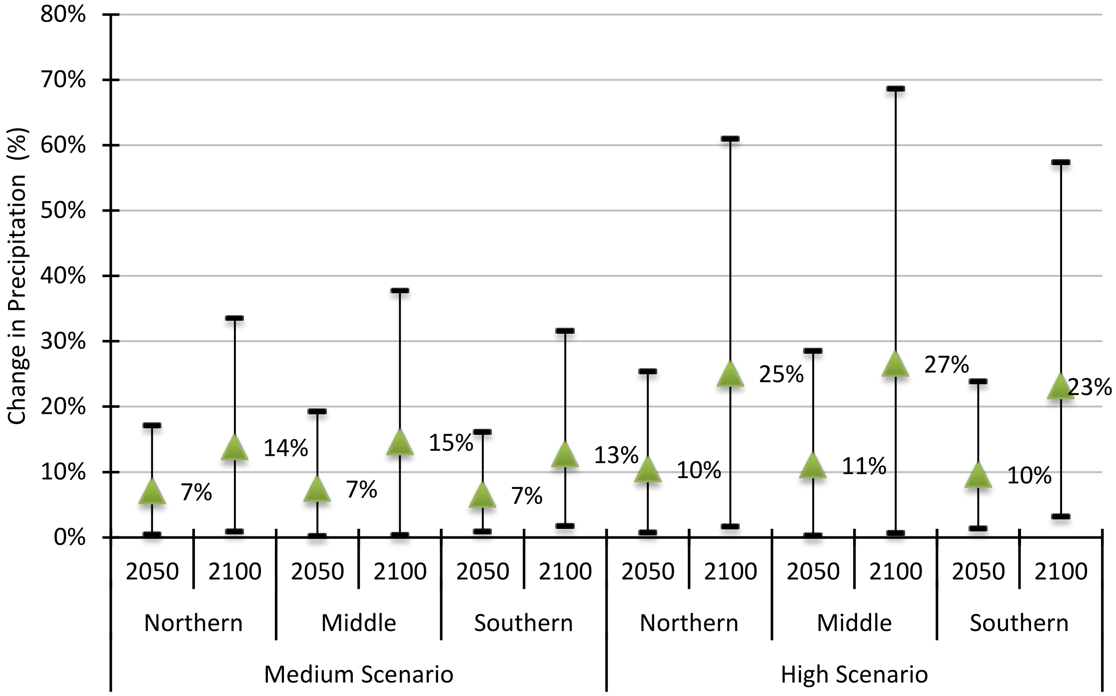


Figure 2.4 Percent Change in Summer Precipitation by Scenario, Region, and Year

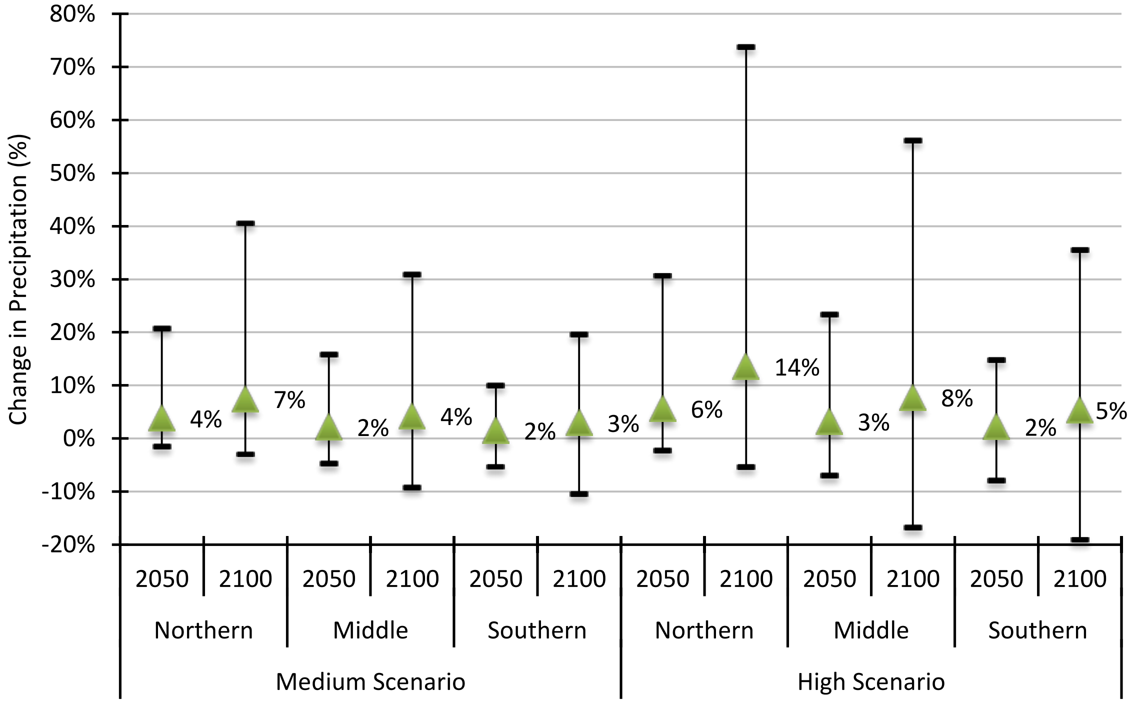
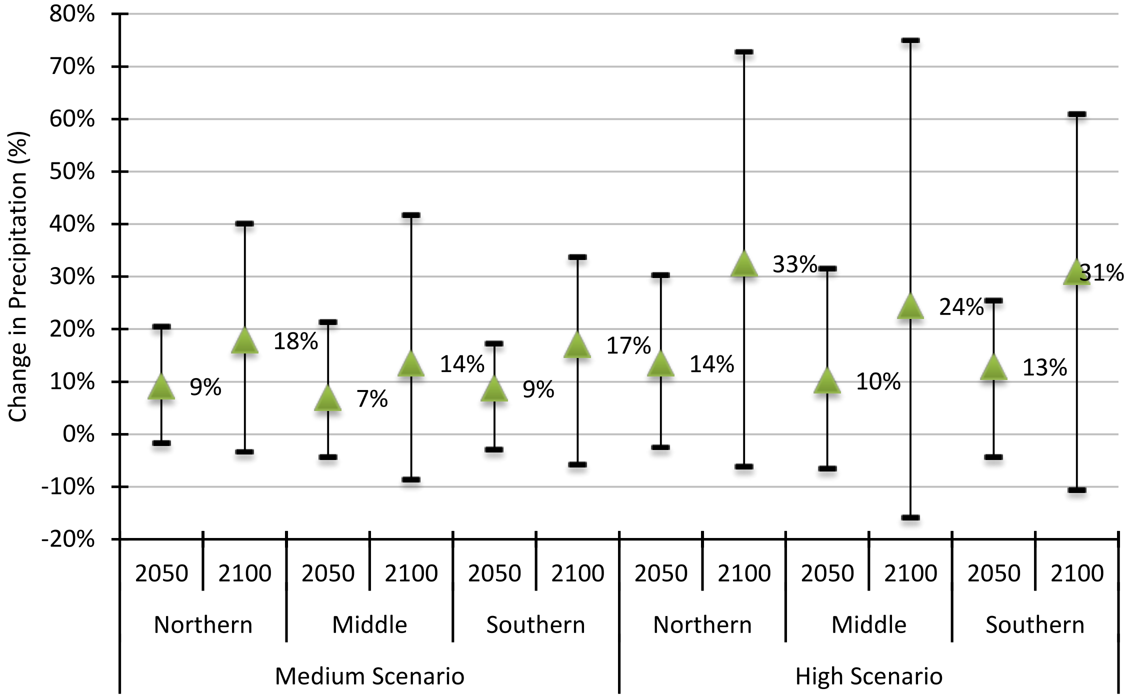


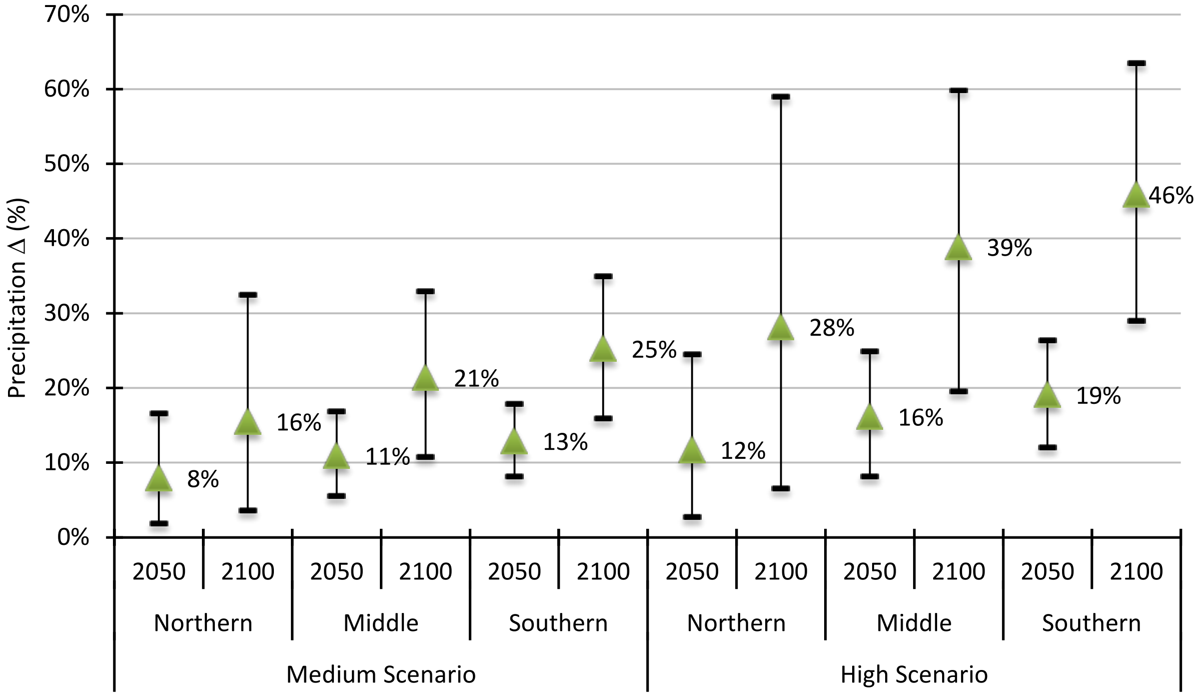
Figure 2.5 Percent Change in Winter Precipitation by Scenario, Region, and Year



Extreme Precipitation Events

The models project an increase in the expected magnitude of 100-year, 24-hour precipitation events over the next century (the storm with a 1 percent likelihood of occurring in any given year), with minimal differences between the three regions (Figure 2.6). The higher emissions scenario shows much more variability in the projections for 2100 (a range of 50 percent) compared to the medium emissions scenario (a range of 20 to 25 percent). Thus, while there is a clear expectation for increased precipitation, the magnitude of that change is uncertain.

Figure 2.6 Change in 100-Year Precipitation Amount by Scenario, Region, and Year



Summary Findings

- Average annual precipitation is projected to continue to increase across Michigan, and much of that increase will be concentrated as winter precipitation; however, there is considerable variation across regions and projection year as to the *amount* of increase.

- The amount of precipitation expected to fall within a 24-hour period for the 30, 50, and 100 year event is expected to increase under the high-emissions scenario. Under this scenario, precipitation is projected to increase by as much as 3-inches (on top of a current average of approximately 4 inches) during a 24-hour, 100-year event by 2100. The medium emissions scenario projects average increases of just over an inch (on top of baseline) during a 24-hour, 100-year event by 2100.

Temperature

The analysis of temperature considered:

- The annual average temperature – mean of the average daily temperature across an entire year;

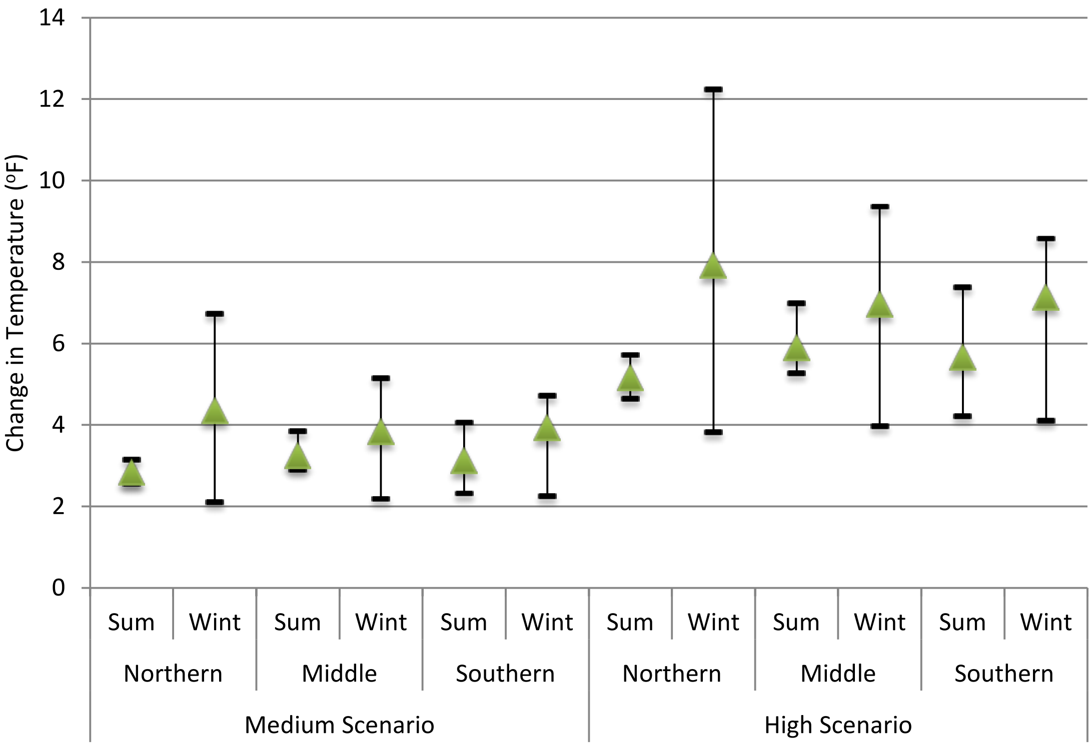
- Minimum – mean of the daily minimum temperature across an entire year; and

- Maximum – mean of the daily maximum temperature across an entire year.

The average, minimum, and maximum annual temperatures in Michigan have increased from 1960 to 2010, on the order of 0.5°F per decade (National Climatic Data Center, 2014). Average, minimum, and maximum winter temperatures have increased at a greater rate over this 50-year period than summer temperatures.

The model projections suggest that the average, minimum, and maximum temperatures will continue to increase under both emission scenarios. The increase in temperature is projected to be similar across the three regions of the State. Under the medium emission scenario, the annual average temperatures are expected to increase by 3.1°F by 2050 and 6.1°F by 2100. Under the high-emission scenario, annual average temperatures are expected to increase by 4.5°F in 2050 and 11.0°F in 2100. The changes in annual minimum temperature and maximum temperature are projected to be similar to the change in average temperature. Seasonally, greater changes in average temperature are expected in the winter months than in summer and in the Upper Peninsula than the rest of the state (Figure 2.7). However, there is much more variation in those winter and northern emissions future temperature estimates.

Figure 2.7 Expected Change in Seasonal Average Temperature by Scenario and Region, 2100



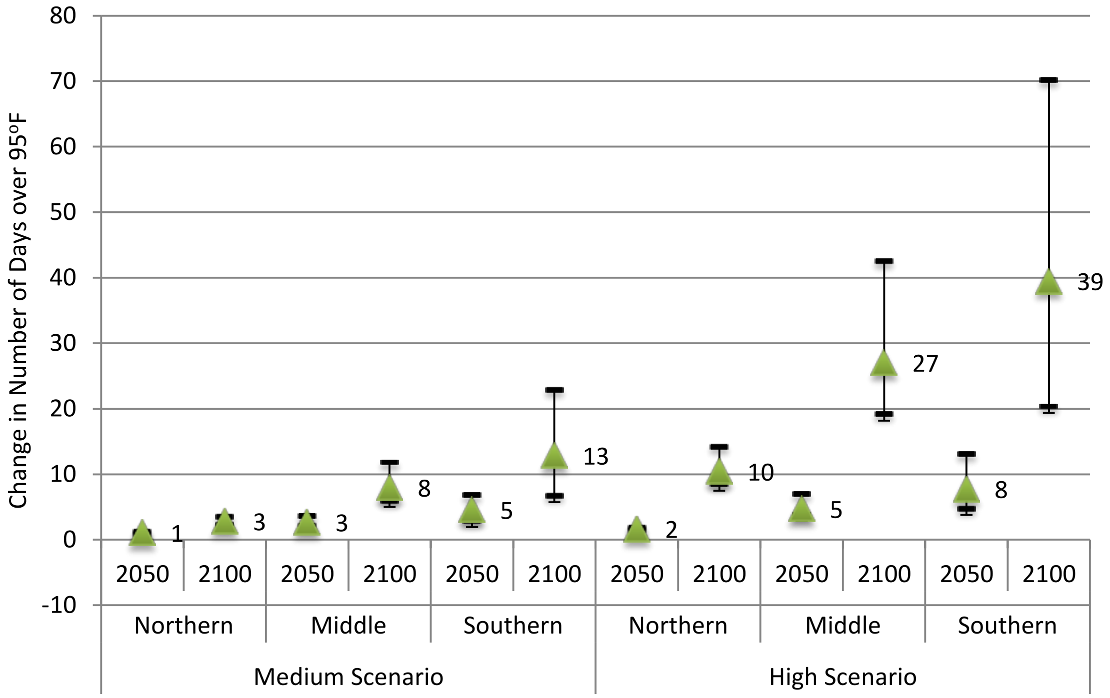
Annual temperatures are projected to increase in a similar manner. However, on average, the models project greater increases in mean and minimum temperatures in the winter than the annual averages, consistent with the past trends discussed above.

More significantly for a climate vulnerability assessment, the study also examined the changes in three extreme weather variables:

- Hot days. The number of days per year over 95°F ;
- Frost Days. The number of days per year below 32°F ; and
- Freeze-thaw days. The number of days per year with a high above 32°F and a low below 32°F.

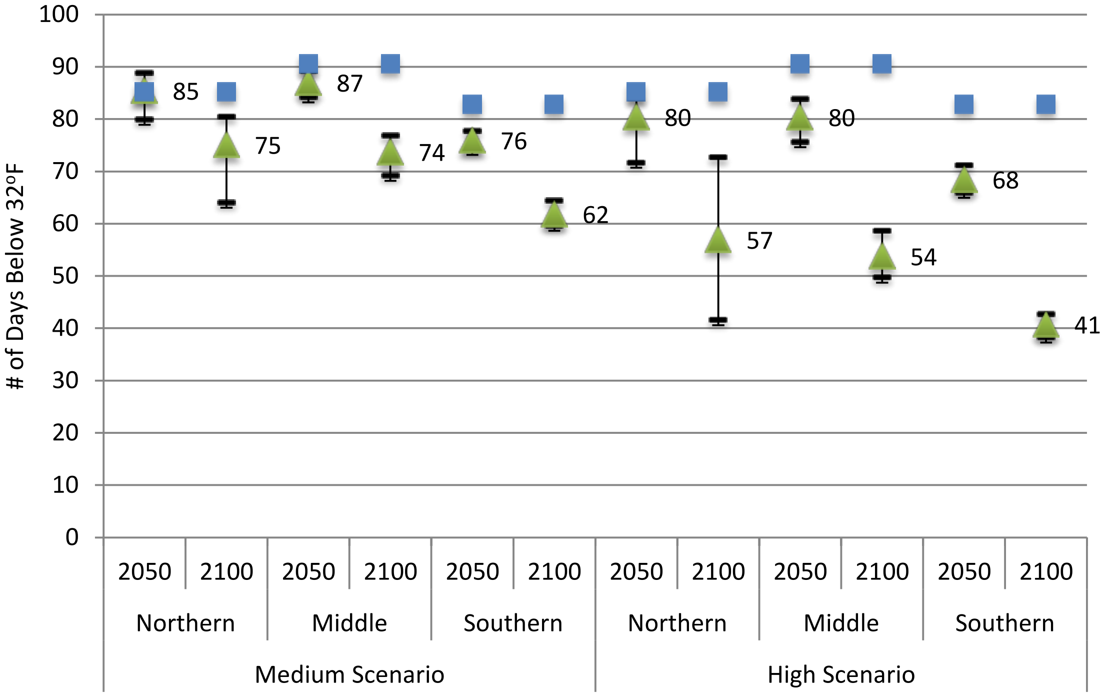
Currently there are very few days that exceed 95°F (hot days) in Michigan, which is a widely used standard of practice threshold for examining extreme heat. For the baseline period, there was less than one hot day per year on average in each of the three regions. Hot days are projected to increase across Michigan under both emission scenarios (Figure 2.8). The greatest increases are projected for the Southern region, followed by the Middle region.

Figure 2.8 Change in Hot Days (over 95 °F) by Scenario, Region, and Year



Both frost days and freeze thaw days are expected to decline significantly in the future. Currently, the northern region of Michigan experiences 86 freeze-thaw days, the middle region 92 freeze-thaw days, and southern region 84 freeze-thaw days (Figure 2.9). Projections from both emissions scenarios were show a slightly smaller decline in freeze thaw days for the northern part of the Lower Peninsula in 2050 than for the Upper Peninsula or Southern Michigan. However, by 2100, the high scenario suggests a rapid decline in the number of freeze thaw days across the board.

Figure 2.9 Number of Frost Days by Scenario, Region, and Year



Note: Blue boxes represent the current average regional number of frost days.

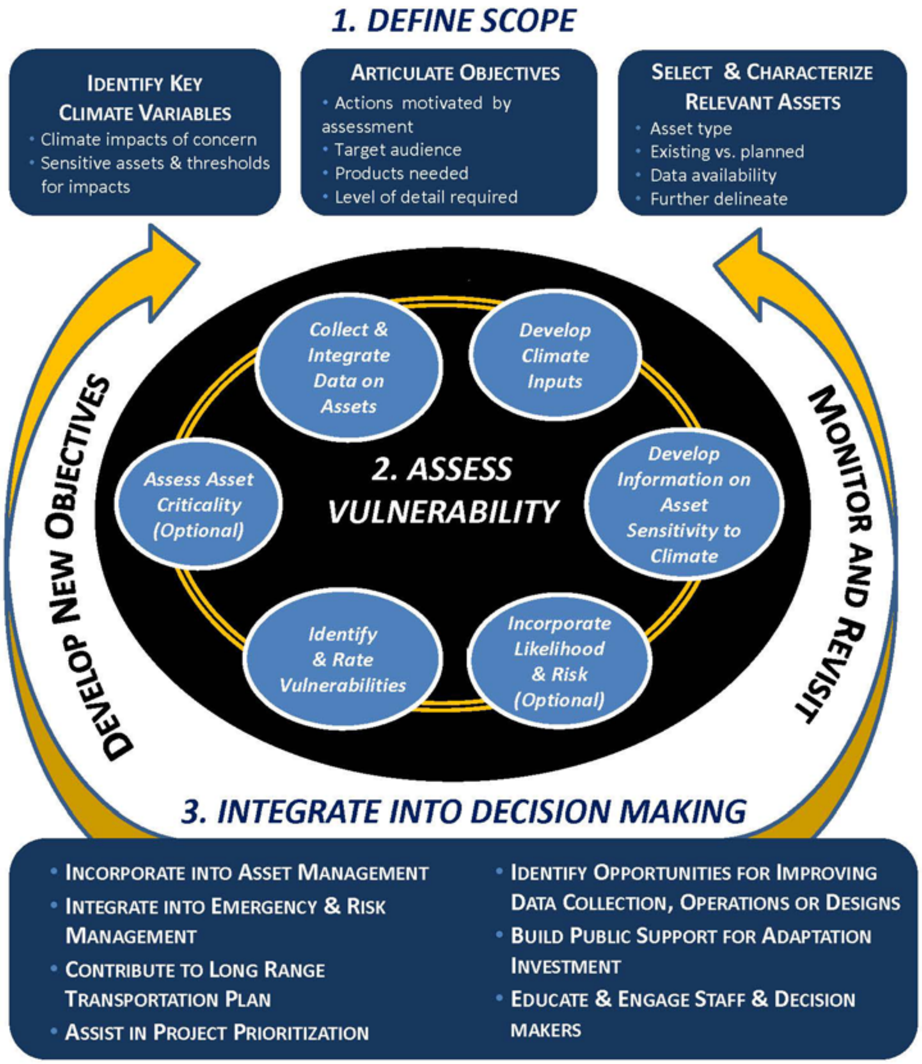
Summary Findings

- Average annual temperatures in Michigan are projected to increase, and at a greater rate in winter.
- In general, the average number of Freeze-thaw Days and Frost Days are projected to decrease by 2050, and continue to decrease at a faster rate by 2100. These changes are projected to occur at a greater rate in the southern portion of the State.
- The number of annual Hot Days is expected to increase, but is not expected to increase dramatically until after 2050.

3.0 ASSESSMENT PROCESS

The criticality, vulnerability, and risk assessments comprised a significant portion of the project. These built on by the FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework introduced in Section 1. The second step of the Federal Highway Administration (FHWA) Climate Change and Extreme Weather Vulnerability Assessment framework (Figure 3.1) guided the analysis of future vulnerabilities to climate change. Following this framework, the team used a Geographic Information Systems (GIS) platform to perform a vulnerability assessment of MDOT transportation assets to extreme precipitation and extreme heat.

Figure 3.1 FHWA Framework for Assessing Climate Change and Extreme Weather Vulnerability



Source: FHWA.

An assessment of asset criticality focused on the consequences of removing an asset from service, and assigned criticality scores according to an asset's relative importance to the transportation system as a whole. Next, the determination of potential vulnerability (exposure in particular) was made by overlaying transportation asset data – chiefly the location of each asset – with projected changes to two climate stressors: extreme precipitation, and extreme heat. A batch geoprocessing technique was used to facilitate the efficient intersection analysis of multiple asset types and emissions scenarios. Finally, each asset was assigned an overall risk score corresponding to each climate stressor/climate model/emissions scenario/year combination.

This analysis was conducted statewide for all MDOT-owned bridges, trunk line roadways, pumps, and culverts for which MDOT geodata were available. The multiplication of the exposure and criticality scores yielded a risk score for each asset. A detailed methodology for each of these assessments is discussed below.

3.1 Assessing Vulnerability

Vulnerability of assets to extreme weather is typically measured using three factors:

- **Exposure** captures the direct and indirect impacts of extreme weather based primarily on an asset's location;
- **Sensitivity** captures the ability of an asset to continue functioning when exposed to an impact.
- **Adaptive capacity** captures the ability of a system to continue functioning at an acceptable level of performance.

The statewide scale and data limitations of the vulnerability assessment approach resulted in an analysis that best captured an assets potential exposure to future climate risks. More detailed information, such as high resolution elevation data and flood hazard data, are necessary to properly assess a particular assets sensitivity or adaptive capacity to a particular climate threat. While the report focuses on exposure, the concepts of sensitivity and adaptive capacity are carried throughout the analysis.

Exposure

The vulnerability assessment examined the expected exposure of MDOT infrastructure to the two climate stressors expected to have the greatest impacts: extreme precipitation and extreme heat. Using GIS software, projections for these climate stressors were intersected with MDOT transportation assets. For each climate stressor, four raw exposure scores were generated. These scores were as follows:

- 2050 medium-emissions scenario;
- 2050 high-emissions scenario;
- 2100 medium-emissions scenario; and
- 2100 high-emissions scenario.

Due to the significant variability in future climate projections across the models, the study team decided to use an average of the five selected climate models. The team tested several approaches to combining the five models into a single estimate but none produced meaningfully different results than those shown here. As such, each raw exposure score represents an *average percent change* (for extreme precipitation), and an *average total number of hot days* (for extreme heat). Climate data were spatially intersected with MDOT transportation assets data for each stressor/emissions scenario/year combination.

Following guidance from the MDOT working group on the sensitivity of infrastructure types to potential climate stressors, raw extreme precipitation scores are based on the following:

- For roadways and bridges, percent change in precipitation quantity constituting 24-hour 100-year event;
- For pumps, percent change in precipitation quantity constituting 24-hour 50-year event; and
- For culverts, percent change in precipitation quantity constituting 24-hour 30-year event.

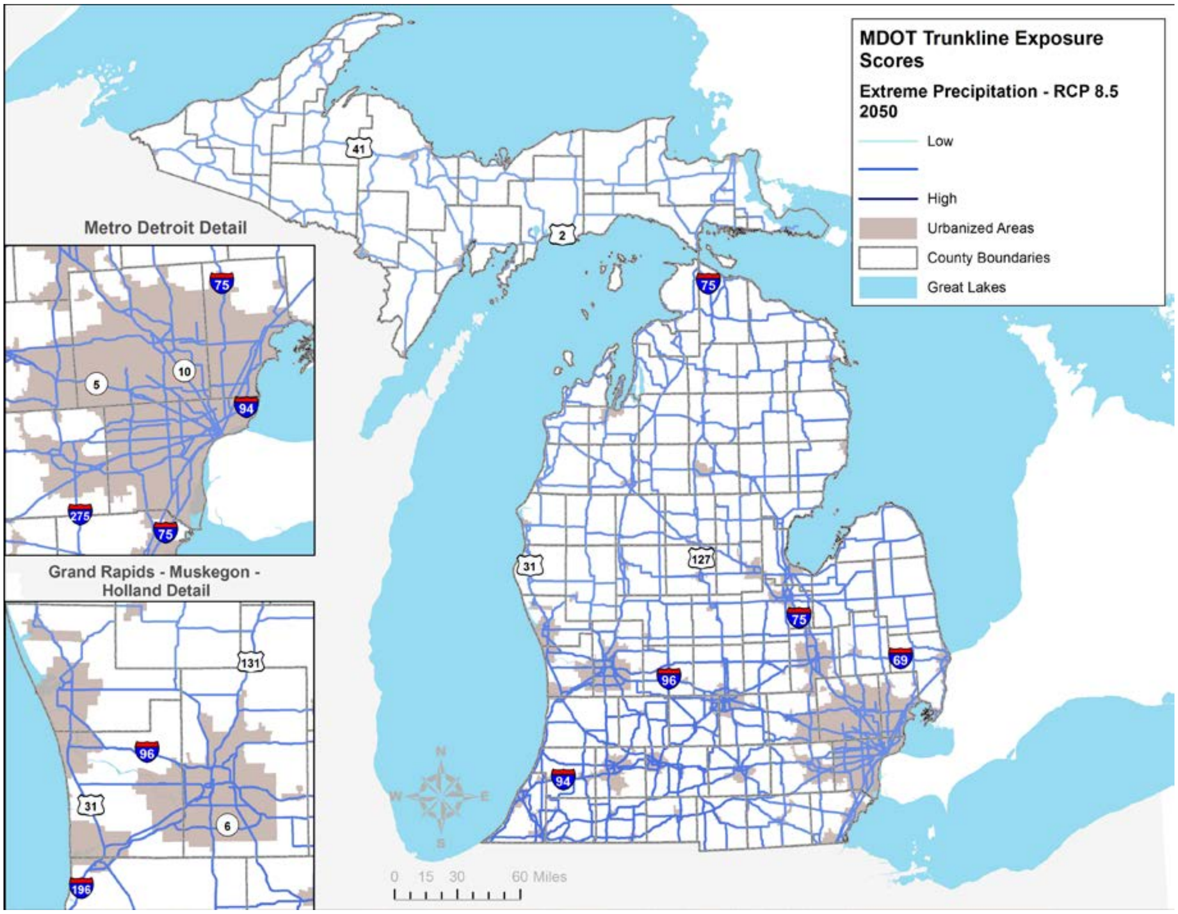
While the extreme precipitation scores represent exposure to increasing precipitation quantities during extreme precipitation events, they do not reflect other data, such as an asset's location within the 100-year floodplain. The Federal Emergency Management Agency (FEMA) is currently digitizing Flood Insurance Rate Maps (FIRM) that will indicate the spatial distribution of the 100-year floodplain for the State of Michigan. Until this information is available as part of the National Flood Hazard Layer (NFHL), approximately 60 percent of the State lacks flood plain coverage. Even though the study team opted to not incorporate 100-year floodplain data into the exposure score itself because of the limited coverage, the team flagged each asset within the NFHL coverage area, as well as those within the 100-year floodplain, in the final vulnerability spreadsheet.

Raw extreme heat exposure scores are based on the number of days with a high temperature above 95 degrees. Pumps and culverts did not receive extreme heat exposure scores. Note that for both extreme precipitation and extreme heat, the projected changes used for the vulnerability assessment represent the *mean* change for the five selected climate models for a given year and emissions scenario.

Final exposure scores were normalized based on the highest value across all scenarios to produce the final exposure scores (out of 100). Exposure scores were calculated for both the medium- and high-emissions scenarios, and for two analysis years – 2050 and 2100 – yielding four individual exposure scores for each asset. Rather than placing scores into categories (low/medium/high), scores were mapped on a continuous scale. For mapping purposes, break points in these scales were identified with the MDOT advisory committee, but the underlying presentation is of a continuous, though not linear, scale. Once final scores were calculated, they were assigned to each asset in GIS.

The vulnerability assessment revealed several notable trends. For extreme precipitation, exposure scores were highest in the southern portion of the State for all emissions scenarios and model years. In general, the south-central and southwestern portion of the Lower Peninsula saw the highest scores, while the northern Upper Peninsula saw the lowest exposure scores. This is consistent with the projected changes to extreme precipitation quantities: southern portions of the State are expected to see the largest changes, percentage-wise, in extreme precipitation quantities constituting the 100-year, 24-hour event. The roadway assets with the highest risk scores (100) were generally located in Branch, Calhoun, Hillsdale, and Jackson counties. This corresponds to a 20 percent increase in 100-year, 24-hour precipitation under the 2050 high-emissions scenario, and a 51 percent increase under the 2100 high-emissions scenario. An example extreme precipitation exposure map for roadways is shown in Figure 3.2. Darker blue shading indicates roadways with expected greater increase in future extreme precipitation.

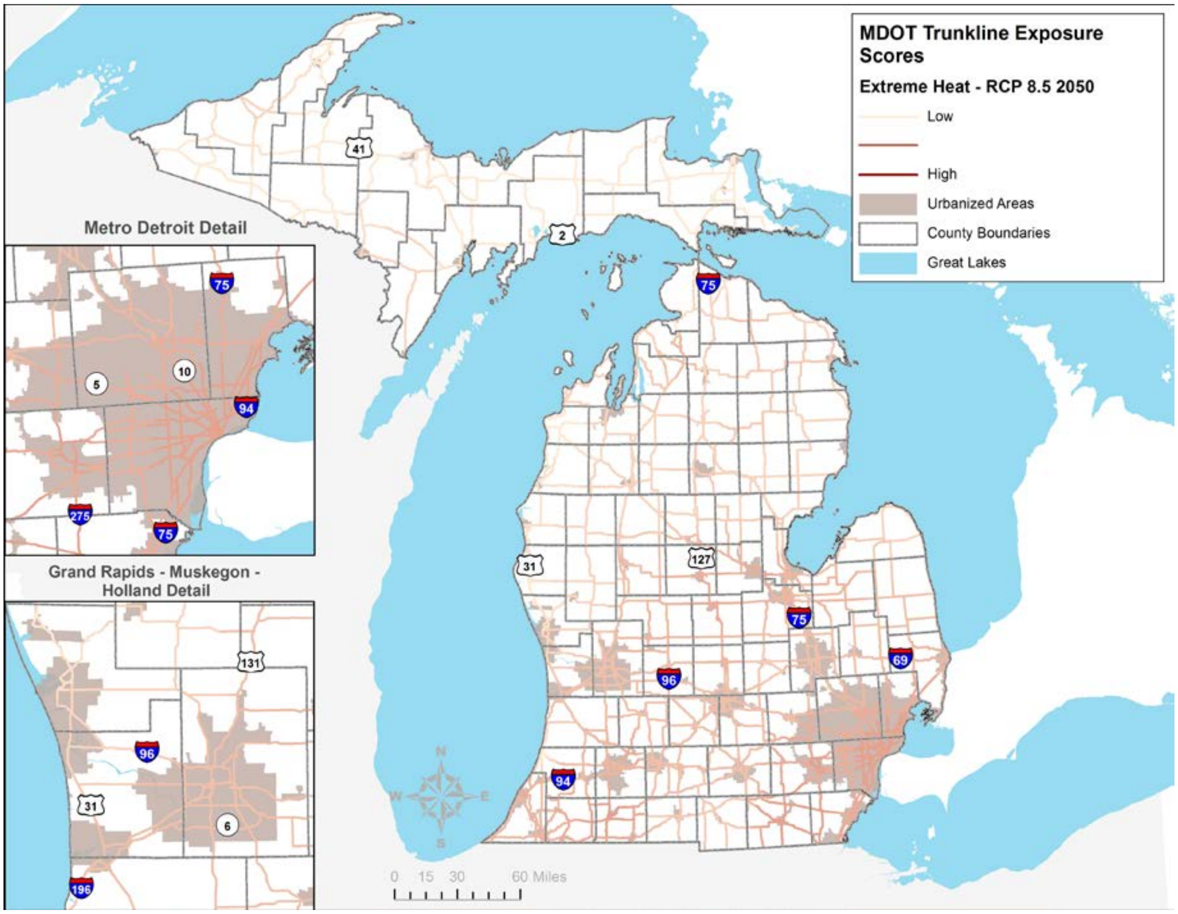
Figure 3.2 Extreme Precipitation Exposure for MDOT Trunk Line Roadways, High Emissions Scenario 2050



Note: Please refer to the separate Map Folio for high-resolution, pan-zoom exposure, criticality, and risk maps.

For extreme heat, vulnerability trends were similar; roadways in the southern portions of the State can expect greater exposure to extreme heat, while the Upper Peninsula will likely experience less extreme heat. Urban areas in the southern Lower Peninsula see the highest scores owing in part to the urban heat island effect. Figure 3.3 displays the extreme heat exposure for MDOT trunk line roadways – darker red shading indicates roadways with higher exposure scores for extreme heat.

Figure 3.3 Extreme Heat Exposure for MDOT Trunk Line Roadways, High-Emissions Scenario 2050



Note: Please refer to the separate Map Folio for high-resolution, pan-zoom exposure, criticality, and risk maps.

Please refer to the Map Folio document for the full set of maps for both extreme precipitation and extreme heat climate stressors.

Sensitivity and Adaptive Capacity

Until such time as necessary data are available to assess sensitivity and adaptive capacity, the impacts of recent extreme weather events on transportation systems and assets provides insight into the tolerance of a particular asset to certain climate stressors. Properly monitored, these events can help determine thresholds at which an asset becomes damaged or begins to deteriorate. This information can in turn inform design thresholds for certain asset types. There is a balancing act between monitoring performance and taking action prior to the failure of an asset. The findings of this risk assessment, combined with further investigation of a particular asset supported by robust data, can help inform when strategic investments are necessary. Presently, the study team recommends continued monitoring of assets projected to experience a heightened degree of exposure. A more in-depth analysis for highly critical assets that appear particularly vulnerable to a specific climate stressor may be needed to address true vulnerability and risk, and to define appropriate adaption strategies. Both of these efforts are beyond the scope of this assessment.

3.2 Defining Criticality

A criticality assessment generally focuses on the consequences of removing an asset from service. This assessment of transportation asset criticality provides a basis for establishing which assets provide the greatest contribution to regional mobility and/or economic activity. Asset criticality was used as one of two components to determine risk.

The criticality assessment was built on a scour criticality assessment performed by MDOT on trunk line bridges that traverse waterways. This assessment includes a score for criticality based on the following weighted factors:

- Traffic volume;
- Functional classification;
- Detour length;
- Cost of replacement; and
- Economic impact (truck volumes and presence of marine navigation).

The study team used this as the basis for the criticality analysis, and replicated it for all MDOT bridges using data from the National Bridge Inventory (NBI).

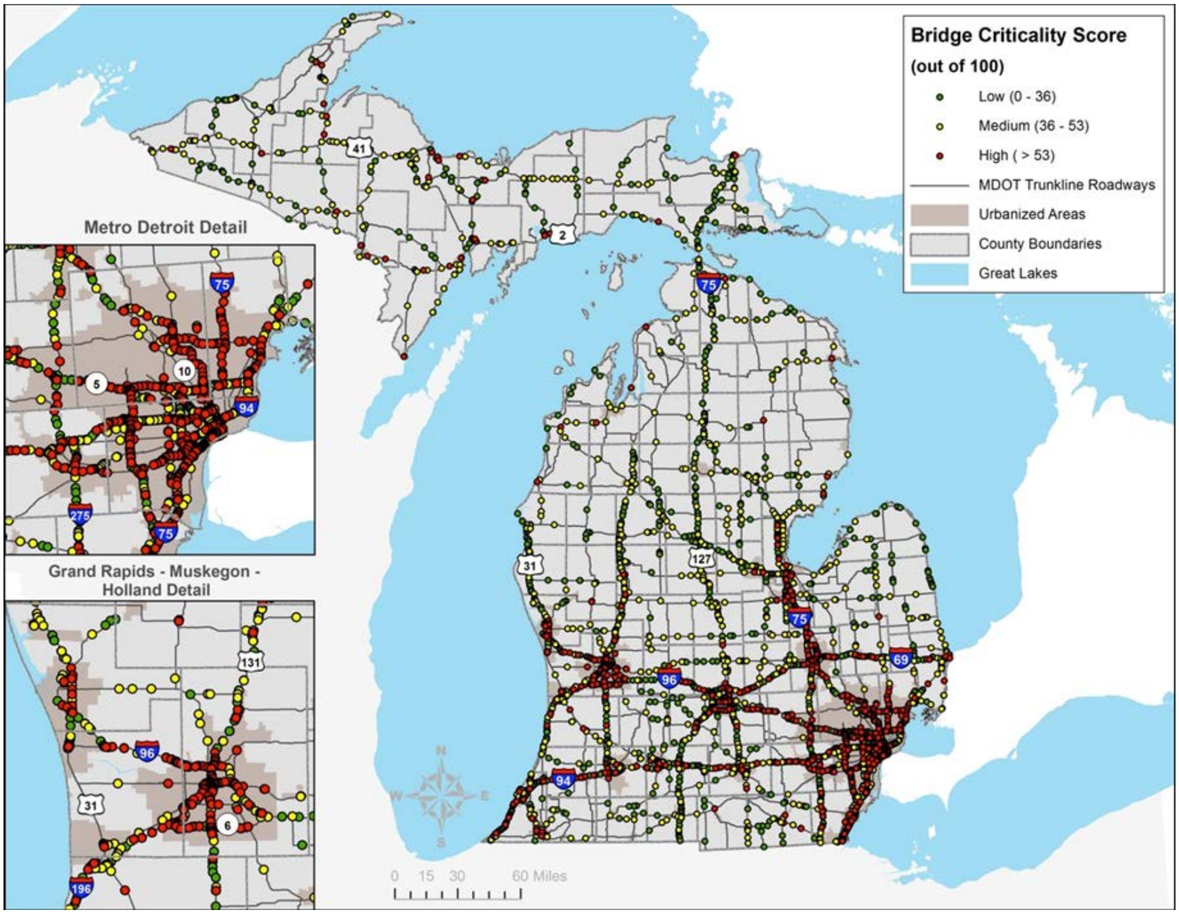
A separate criticality assessment was completed for trunk line roadways using a similar methodology. As with bridges, roadway criticality scores are based on the following factors:

- Traffic volume (highest weight);
- Functional classification;
- Cost of replacement:
  - Based on average reconstruction cost by functional class and urbanization from the Highway Economic Requirements System – State (HERS-ST) model.
- Economic impact (truck volumes).

Note that detour length was not incorporated in to the roadway criticality scores. Estimating detour length for roadway segments is not as simple as it is for bridges, which are a fixed point.

Final criticality scores were recalculated on a scale from 0 to 100. Similar to the original MDOT scour criticality spreadsheet, one-third of assets were placed into each of three categories: low, medium, and high. An example criticality map for bridges is shown in Figure 3.4. Please refer to the Map Folio for the full set of criticality maps.

Figure 3.4 Bridge Criticality



Note: Please refer to the separate Map Folio for high-resolution, pan-zoom exposure, criticality, and risk maps.

4.0 ASSESSMENT RESULTS

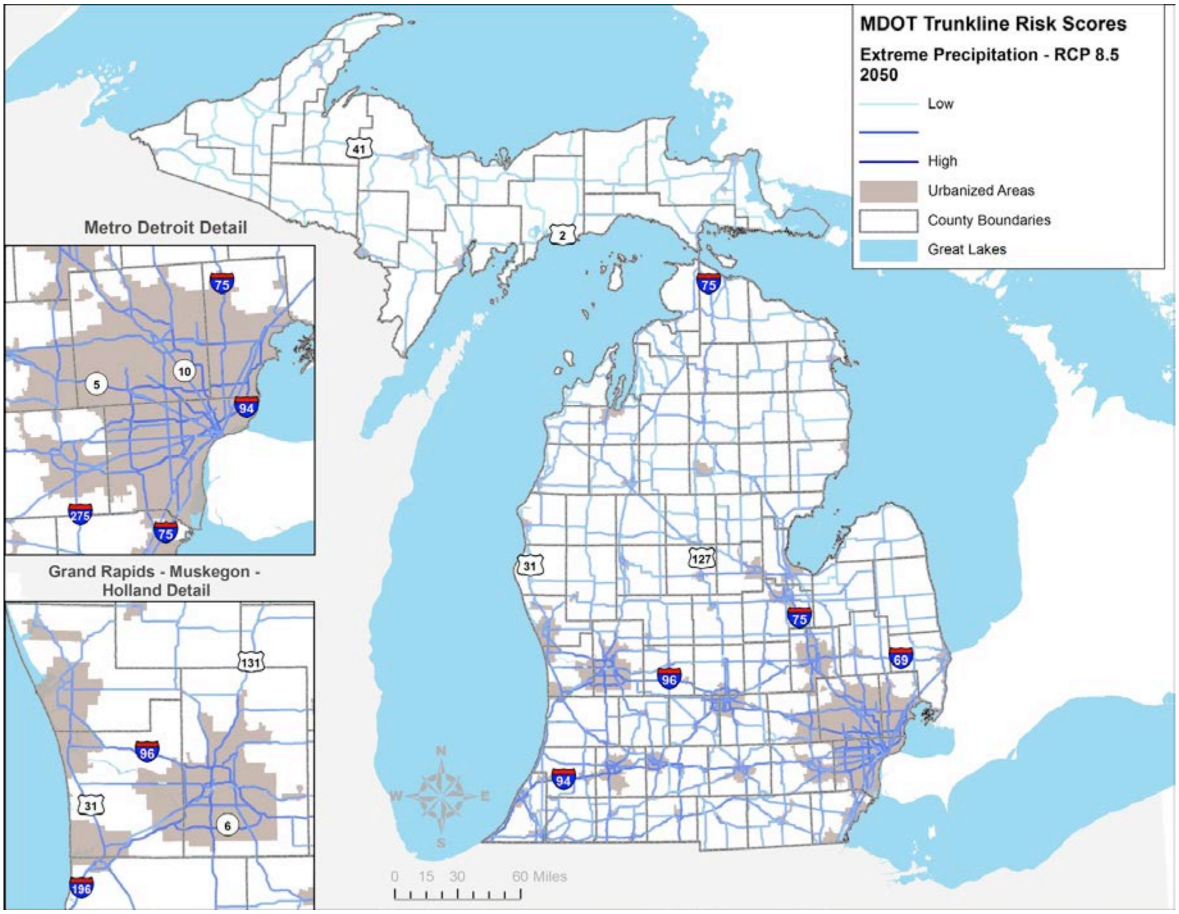
4.1 Statewide Risk Analysis

After completing the criticality and vulnerability assessments for all MDOT-owned trunk line roadways, bridges, pumps, and culverts, the study team performed a preliminary statewide risk assessment for these assets. Rather than adding criticality and vulnerability scores together to produce the risk score for a given asset, the study team instead multiplied the two scores together. This focused the analysis on the most at-risk and critical assets. Final scores were normalized to a 0 to 100 scale and were produced for each model year and emissions scenario, resulting in four risk scores for extreme precipitation, and four for extreme heat. There was significant consistency in the pattern of risk shown by each of the risk scores. Because one scale was used for all for scores, the magnitude varies across the scores, but follows a similar pattern.

The scores presented in this analysis only tell one part of the risk story. Additional information about sensitivity of assets and adaptive capacity of the system is needed to fully understand risk, but these data were not available statewide. Particular additional data needs are described in more detail in the focused risk analysis in Section 4.2. The scores generated here are one important dimension of risk, but additional complementary information will be needed to inform decision making.

The results of the statewide risk assessment for extreme precipitation and extreme heat reveal several notable trends. Much like the vulnerability assessment inputs, most of the highest-risk assets were located in the southern portions of the State. For extreme precipitation, the highest-risk roadways were generally found in and around the major metropolitan areas in the southern third of the Lower Peninsula, as shown in Figure 4.1. As with the vulnerability/exposure maps discussed in Section 3.1, darker blue shading indicates roadways with higher risk scores.

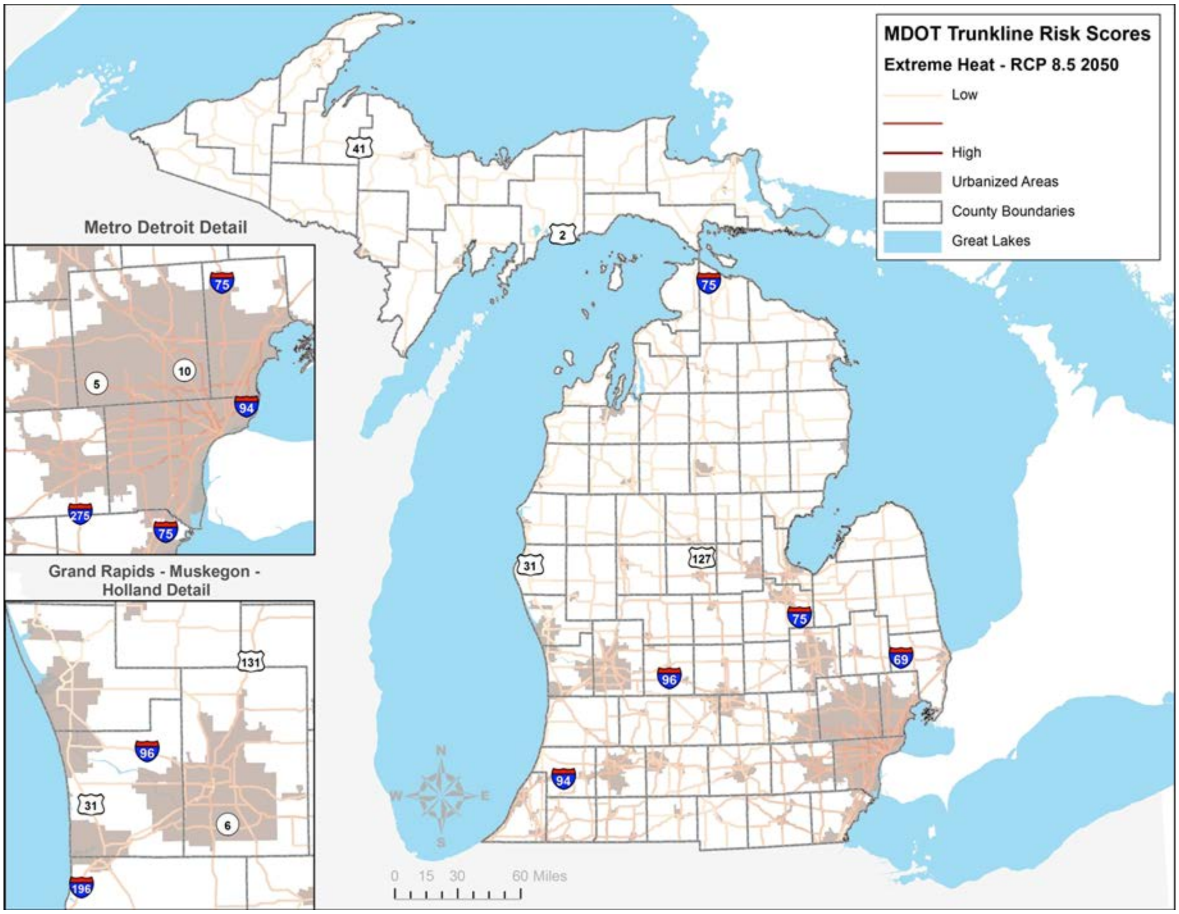
Figure 4.1 Extreme Precipitation Risk for MDOT Trunk Line Roadways, High-Emissions Scenario 2050



Note: Please refer to the separate Map Folio for high-resolution, pan-zoom exposure, criticality, and risk maps.

The extreme heat risk assessment yielded similar results to that for extreme precipitation. Risk scores for 2050, however, were much lower than their extreme precipitation counterparts. Because all final risk scores were reclassified based on the highest overall score across all model years and emissions scenarios (the highest scores for both stressors came from the 2100 high scenario), this is indicative of the significant uptick between 2050 and 2100 in the expected number of days above 95 degrees. Additionally, the roadways with the highest risk scores for extreme heat are generally found in the Detroit area. This finding is a function of both the relatively high exposure scores in this area (due to the urban heat island), as well as the high criticality of these roadways. Extreme heat risk assessment results for the 2050 high-emissions scenario are shown in Figure 4.2.

Figure 4.2 Extreme Heat Risk for MDOT Trunk Line Roadways, High-Emissions Scenario 2050



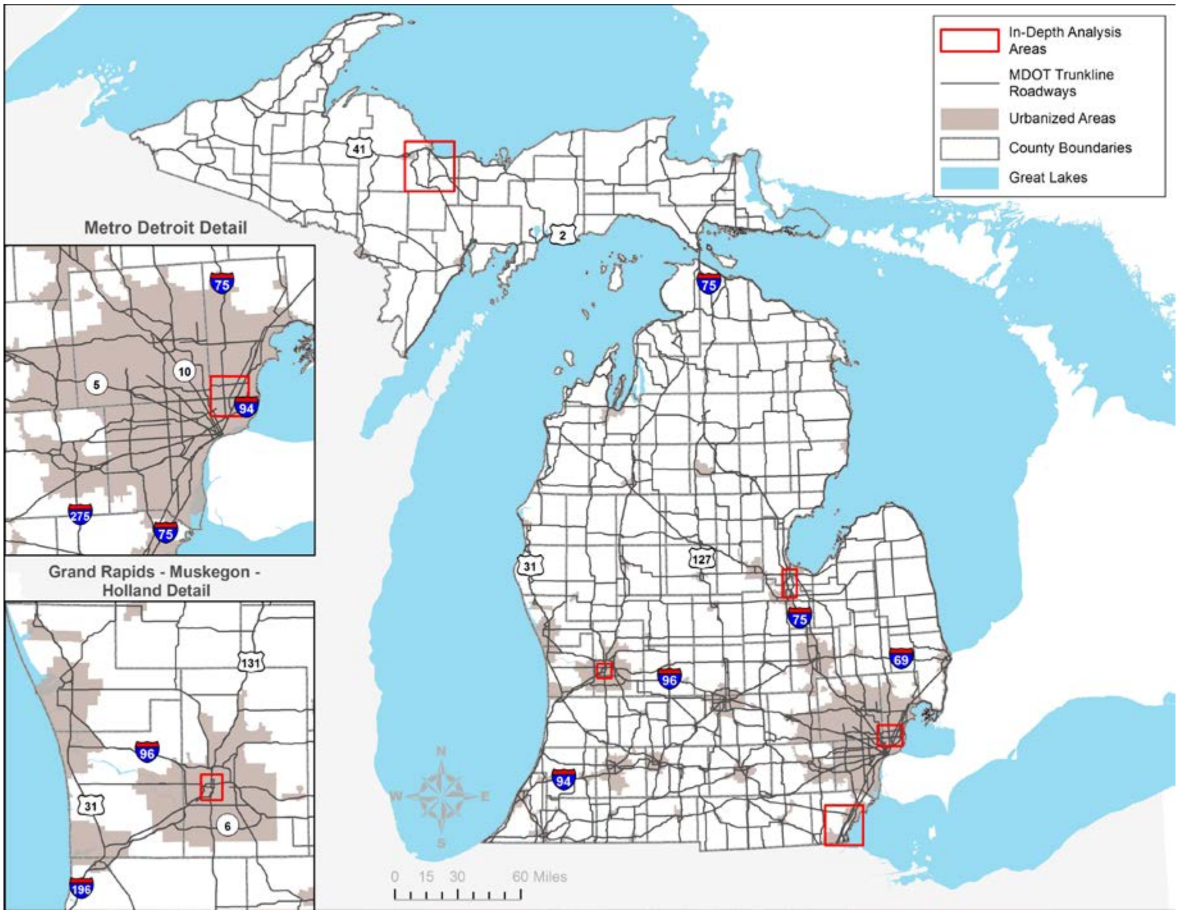
Note: Please refer to the separate Map Folio for high-resolution, pan-zoom exposure, criticality, and risk maps.

Please refer to Appendix C for the complete set of risk assessment maps; high-resolution maps can be found in the separate Map Folio.

4.2 Focused Risk Analysis

During the October 16th, 2014 meetings of the TAC and MDOT working group, the study team facilitated an interactive exercise in which findings from the risk analysis were overlaid spatially with MDOT asset data at a refined scale and discussed. The purpose of the exercise was illustrate the exposure, criticality and combined risk score for certain asset types in order to identify opportunities for planning and decision-making, and document information needed for future assessment of specific assets or asset types. Participants were asked to discuss the results of the risk findings for asset management purposes, and identify missing data (if any) that would be necessary to conduct a more detailed analysis for the highest risk assets. A total of five study areas were examined. The locations of each study area are shown in red in Figure 4.3.

Figure 4.3 Study Areas for In-Depth Analysis



For each of the study areas, the team and the MDOT working group, and the technical advisory committee assessed how well the exposure scores helped assess the vulnerability of assets in the study area, what other information was needed to provide a comprehensive description of vulnerability (including sensitivity and adaptive capacity), and how MDOT could use these or similar results to work with partners on these issues in the future.

Study Area 1 – Grand Rapids

The study area selected for Grand Rapids was approximately 5 square miles and included 5 MDOT-owned bridges from the scour critical database and several local bridges (Figure 4.4). Exposure to extreme precipitation events was assessed for the medium and high emissions scenarios (2050) and corresponding risk calculated.

Figure 4.4 Grand Rapids Case Study Area

Following the approach for describing vulnerability defined in Section 3.1, the following findings were identified:

- Exposure. Expected risk from climate exposure was similar for these assets, based on the available climate data.

- Sensitivity. Additional data that are critical to support a more robust vulnerability analysis were not available or unavailable at a statewide scale, including floodplain data (not available in a digitized format for this area) and refined elevation data. These data could help the participants better understand the sensitivity of these assets to climate impacts.

- Adaptive capacity. The state highway network in this area is part of a larger transportation network that could be put at risk from increased average and extreme precipitation. TAC and MDOT working group members noted that the local system is likely at higher risk with generally lower elevation bridges in this area. Land use data would have been particularly valuable to assess the access being provided by the transportation system

- Other. TAC members noted that there were existing flood wall issues causing flooding inside of commercial buildings along the river. Again, land use data would be helpful, as would information on impacts on other infrastructure.

TAC members identified partnering with local and regional agencies in the area to examine potential extreme weather impacts across multiple types of infrastructure as a useful next step. Gathering more complete flood plain, elevation, and land use data, along with are more focused examination of a particular area should help identify risks in a more robust way.

Study Area 2 - I-75 Corridor, Monroe County

The I-75 corridor study area from Monroe City to the Michigan/Ohio border was approximately 135 square miles and was identified for roadway and drainage system analysis by MDOT (Figure 4.5). This study area was selected, in part, because of a pilot study MDOT is conducting of using the FHWA INVEST sustainability analysis tool on the same corridor. Exposure to extreme precipitation events for the medium- and high-emissions scenarios (2050 and 2100) were used to depict risk along the roadway.

Figure 4.5 I-75 Case Study Area

Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Following the approach for describing vulnerability defined in Section 3.1, the following findings were identified:

- Exposure. Expected risk from exposure to climate was similar for these assets, with most of the variation in the risk scores based on criticality of different assets, with I-75 receiving higher average criticality ratings than the other two facilities. At the time of this report, contiguous floodplain maps were being developed by FEMA for this area. Once available, these data could be factored into the risk analysis, likely heightening the exposure risk of select assets that intersect with these zones.

- Sensitivity. In addition to the bridge and roadway risk scores, the map also provides information on the location of culverts along US 24 and M-50.[2] While not revealing in itself, the lack of culverts suggests the significant sensitivity of many of MDOT's assets to extreme weather events. The culverts indicate the amount of water already being moved across these roads and the need to manage that. Additional data on flood plains and roadway elevation may be useful to help understand sensitivity.

- Adaptive capacity. I-75 is one of three major north-south highway facilities in this region. The existence of other facilities may provide some adaptive capacity, but I-75 is likely to be more resilient to extreme precipitation events than US 24 or M-125. Much of the land use in the area is agricultural, providing above average support for adaptation compared to urbanized areas.

Flooding along this corridor is an issue of concern to MDOT. To begin to address this concern, MDOT could work with local partners to secure digitized floodplain data from FEMA (once available) as well as enhanced elevation data. The Southeast Michigan Council of Governments (SEMCOG) also has LiDAR data available for this area, which would provide high resolution terrain and elevation data that can be helpful in understanding the likely exposure and sensitivity of assets to increased precipitation. The combined floodplain and enhanced resolution elevation data, geospatially intersected with the climate data developed in this analysis, would provide greater precision to this vulnerability analysis and would help MDOT define particular strategies that may make investment in this corridor more sustainable over the long term. Manipulating LiDAR data can be a significant undertaking, so would probably be best focused on limited areas that demonstrate the need for further analysis.

Study Area 3 - Detroit

The Detroit study area identified was approximately 112 square miles and included portions of Macomb and Wayne Counties where a recent heavy precipitation event caused significant flooding of several freeways, including I-696 and I-94 (Figure 4.6).

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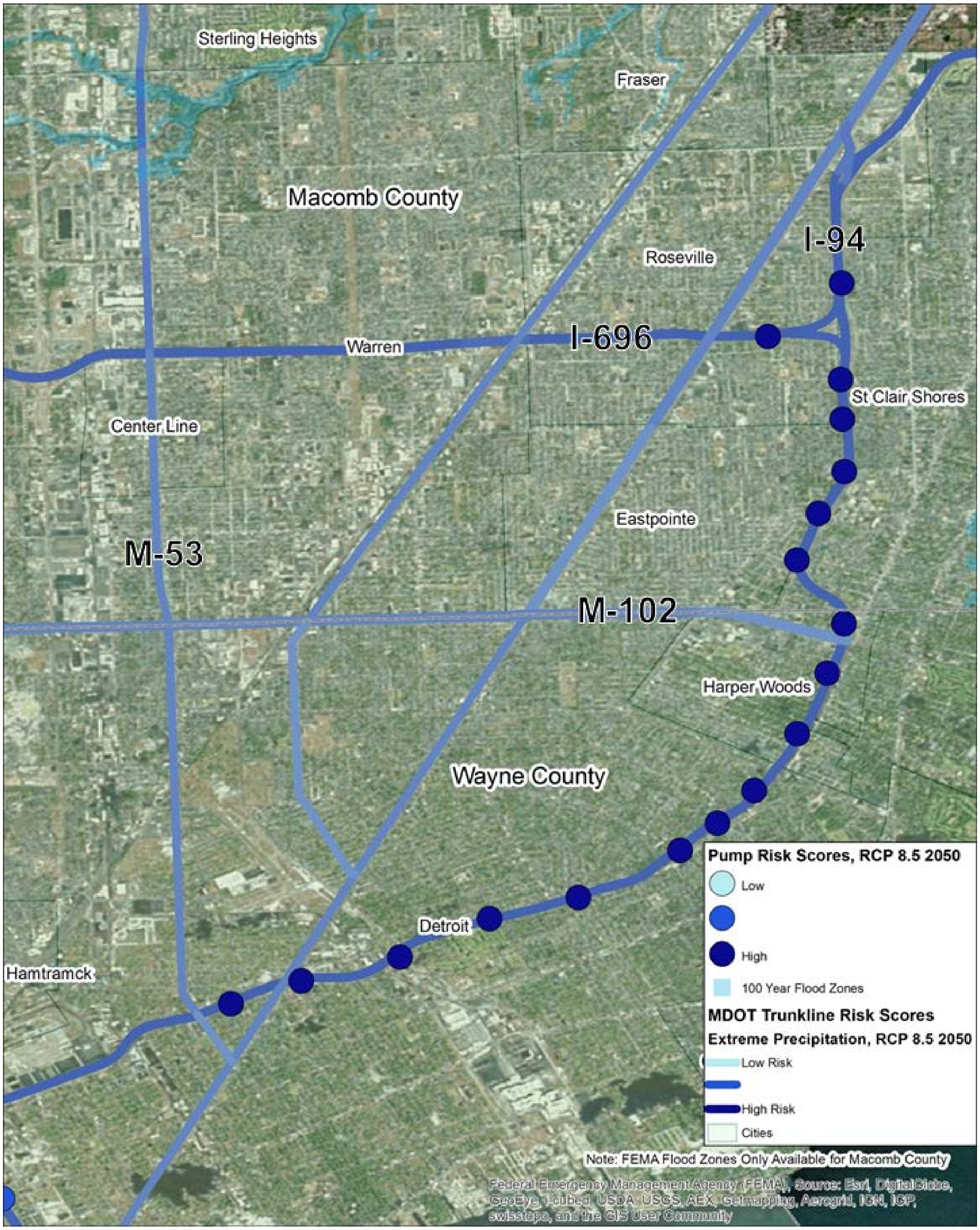
[2] Note that there are no data for culverts identified on M-125, but that is likely due to the lack of data, not the absence of culverts.

Figure 4.6 Detroit Case Study Area



Following the approach for describing vulnerability defined in Section 3.1, the following findings were identified:

- Exposure. The study team examined criticality and exposure scores for the roadway and associated drainage system (primarily pumps), and found there to be sufficient information to support the decision-making needed to mitigate the high-risk pump infrastructure in this area. Because these pumps serve freeways with high auto and truck traffic volumes, they are particularly critical components of the Detroit-area transportation infrastructure.

- Sensitivity. The pumps in the highway system are designed to handle the 50-year storm event; the fact that the rainfall amount constituting the 50-year event is projected to increase, potentially significantly, over the existing 50-year baseline highlights the sensitivity of these assets. Additionally, many of the pumps are past their design life and in poor condition. The recent flooding event is likely to repeat with increased frequency.

- Adaptive capacity. The freeways in this area have limited ability to adapt to increased precipitation. While the pump system could be improved, the pumps are limited in effectiveness by not having a place to transfer water. Pumps connect to Detroit's sewer and drainage system, and MDOT's current contract limits the volume of water to the current pump capacity. Finding additional stormwater storage capacity in Detroit would require significant investment and would be a major engineering challenge. Additionally, since many of the freeways in the Detroit region are sub-grade and rely on pumps to remain free of standing water, there are few alternate routes should several freeways be simultaneously impacted.

Addressing the pumps in the Detroit metropolitan area is a relatively obvious strategy to limit the impact of extreme weather on the Detroit transportation system. But a straightforward solution is not immediately forthcoming. A pump system with more capacity may be part of the solution, but would require a corresponding increase in stormwater capacity. Other solutions would require significant levels of investment that are beyond MDOT's ability to deliver.

Route 13, Saginaw to Bay City

The Saginaw study area was approximately 24 square miles and includes M-13 adjacent to the Saginaw River (Figure 4.7). The study team focused on the exposure to extreme precipitation events and projected risk scores for two bridges and the overall roadway.

Following the approach for describing vulnerability defined in Section 3.1, the following findings were identified:

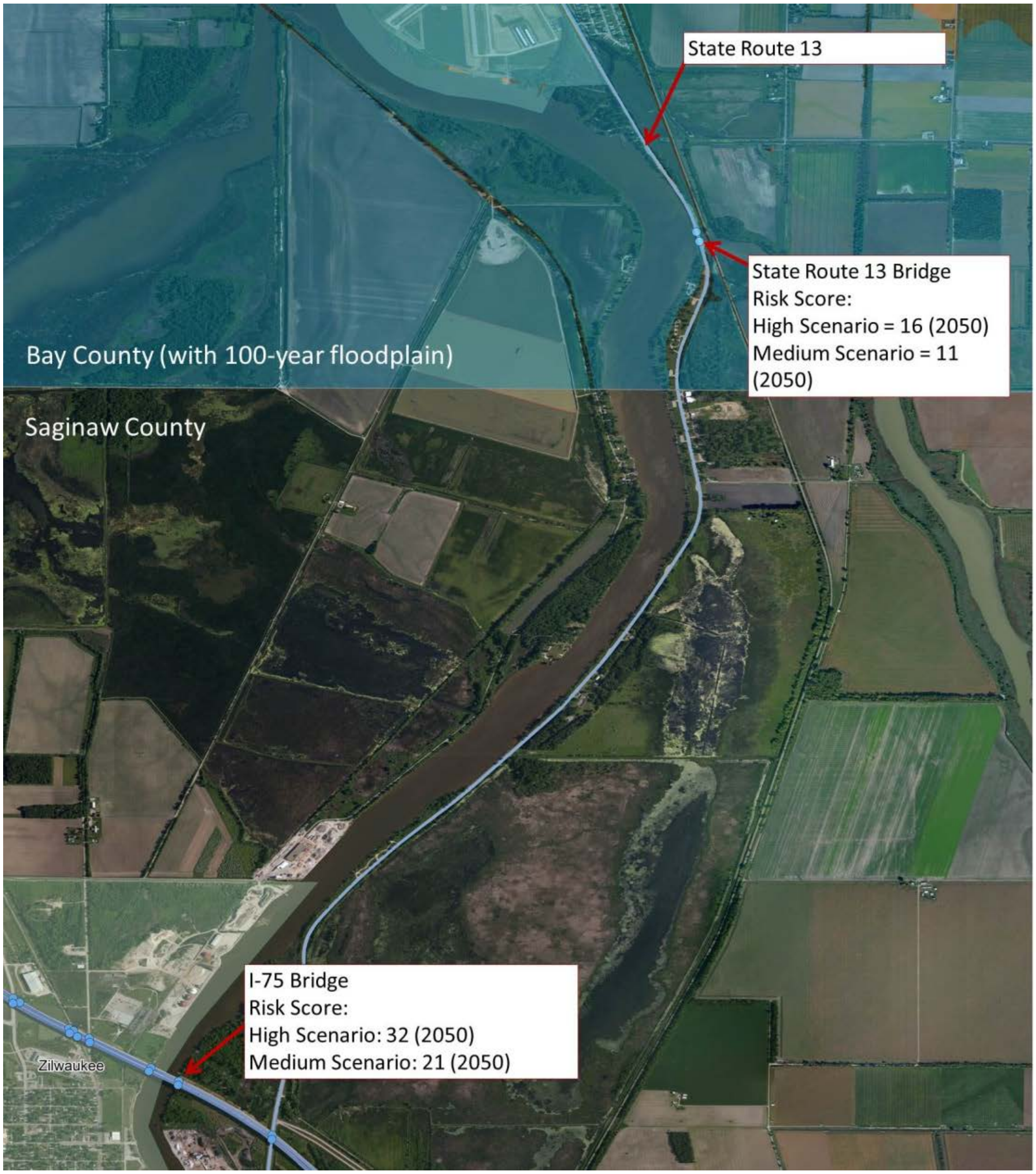
- Exposure. The location of M-13 adjacent to the Saginaw River creates significant potential exposure to climate risk, due to potential erosion and other flooding-related issues. However, both the roadway and the bridges show relatively low risk scores due in part to lower than average criticality scores (mainly due to low traffic volumes), and in part due to (modest) expected increases in precipitation in this area. Floodplain data, while available, was also not factored into the risk score.

- Sensitivity. FEMA floodplain data is available for Bay County, the northern portion of the study area, but it is not available in a digitized format for Saginaw County to the south. Notably, the 100-year floodplain shown for Bay County extends well beyond the boundaries of the map. Much of Michigan has limited elevation changes, making infrastructure sensitive to increases in precipitation. Better understanding of elevation, an in-depth review of the location of the roadway relative to the river, and an identification of other infrastructure (e.g., piers to support the road) would improve an understanding of the sensitivity of the road to increases in precipitation.

- Adaptive capacity. M-13 runs parallel to I-75 further away from the river. Some travel between Saginaw and Bay City may be able to be supported through other infrastructure, but local trips and access to the James Clements Airport may be impacted. Better understanding of the significance of the airport and local land use data may help refine the understanding of adaptive capacity for this road.

This exercise illustrated the influence of traffic volumes in the current risk scores for multiple assets within the study area. For instance, an elevated, newer bridge along I-75 has a higher risk score than an older structure closer to the water level. Elevation data and structure age would help refine the existing information to provide a more robust understanding of risk. Even without these items, the available flood plain data demonstrates that this infrastructure is likely to be very sensitive to increased precipitation. One general finding is that, with significant expanses of flat land, much of Michigan's highway infrastructure is sensitive to increases in extreme precipitation, and that additional information on elevation and slope river stability is particularly valuable in riverine corridors.

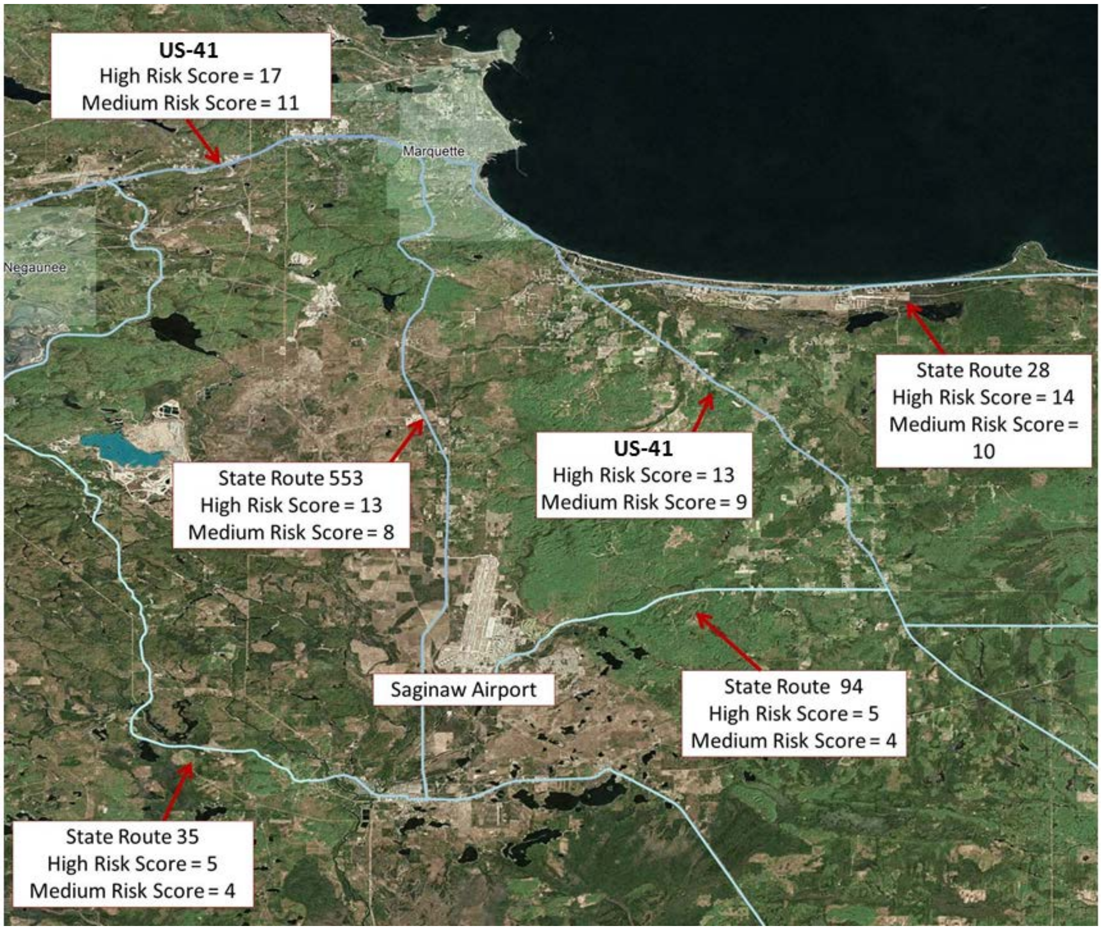
Figure 4.7 Saginaw/Bay City Case Study Area



Marquette County

The study area for Marquette County was approximately 1,000 square miles (Figure 4.8), covering the entire county. The study team identified risk scores for major roadways in the county from extreme precipitation events to better understand at risk areas and alternate route possibilities.

Figure 4.8 Marquette County Case Study Area



Following the approach for describing vulnerability defined in Section 3.1, the following findings were identified:

- Exposure. The team found that the roadways in the area with the highest risk scores were also the most critical for access to Marquette—all roadways connecting to the city saw "High" emissions scenario risk scores of 13-17, with the highest score on US-41 west of Marquette. While increases to extreme precipitation events are expected to be smaller in the Upper Peninsula compared with areas of the southern Lower Peninsula (resulting in lower exposure and risk scores in this region), steeper topography may make flooding during these events more acute in localized areas.

- Sensitivity. Similar to the statewide analysis scale, there is little information at the county-wide scale to assess the sensitivity of infrastructure. This scale of analysis can help focus on some critical connections that may deserve more detailed attention. For example, M-53, which connects Marquette to Sawyer International Airport, is likely an important link, providing further vital connections to other parts of Michigan, the U.S., and Canada.

Understanding the sensitivity of this link may be a useful next step in addressing the impacts of climate vulnerability in the Marquette region.

- Adaptive capacity. While several roads connect Marquette to other parts of the Upper Peninsula, the transportation network is relatively sparse and impacts to individual roads are likely to create significant hardship to residents of outlying rural areas. Should US-41 west of the city be taken out of service during an extreme precipitation event, detours (on smaller, two-lane roadways) would be significant—between 10 and 20 miles on County roads. Connections with nearby cities Negaunee and Ishpeming would be seriously impacted with the closure of US-41.

The risks that extreme precipitation poses to infrastructure in the Upper Peninsula may be somewhat lower than those in the Lower Peninsula, mainly due to lower traffic volumes and smaller projected increases to extreme precipitation as the century progresses. However, the risks are still significant, especially in and around population centers like Marquette.

While extreme temperature and extreme precipitation were the primary focus of the statewide vulnerability assessment, the study team also developed climate data for freeze-thaw cycles, frost days and wildfire trends that may be useful to consider when conducting more in depth risk analysis in the Upper Peninsula. Information on these findings is located in Section 2.3 of this report, and in the Climate Analysis technical memorandum (Appendix B).

5.0 NEXT STEPS

There were two primary objectives of this vulnerability assessment: 1) identify climate risks to MDOT's assets, and 2) develop strategies to begin to address those risks within MDOT's asset management program. Once climate risks to MDOT's assets were identified, recommendations and action items were created for integrating the study findings with MDOT's asset management processes. These suggestions range from planning to project development, to construction, to operations and maintenance of the system, and may be acted upon at MDOT's discretion as resources allow. Below are opportunity areas for integrating the study's findings into MDOT's asset management program.

5.1 State Long Range Planning

While increases in extreme weather events are already being experienced in Michigan, the most significant challenges identified in this study occur within the next 50 to 100 years. In the short term, given the uncertainty of future changes (especially to precipitation), MDOT will likely take a watchful waiting approach, continuing to investigate potential impacts and concerns, while preparing for more significant changes to design, construction practices, maintenance, and operations that are likely to come in the future.

Additional potential implementation steps that could be addressed in the long range planning process include:

- Data collection;
- Continued monitoring and capacity building efforts with MDOT partners;
- Integrating climate and resiliency goals into the state long range transportation plan;
- Conducting more detailed corridor studies that help focus and refine the statewide risk analysis conducted here; and
- Developing methods to integrate climate adjusted benefit cost analysis into investment and programming decisions.

5.1.1 Data Collection

A critical first step is to focus on gathering and managing the data needed to provide a more robust assessment of vulnerability. The analysis, especially of focused assets, revealed the value of floodplain, elevation, and land use data to better capture the sensitivity of assets to extreme weather impacts and adaptive capacity of the transportation system.

While a combination of the three above data items are important for assessing vulnerability, collecting these at the statewide level is overly burdensome. The best of use of these more detailed data items is at a more focused scale – potentially a county, but more likely a specific corridor. At a statewide level, significant information might be lost in generating a single score that identifies risk. Instead, the exposure information generated here can be useful to help point MDOT to information to collect as part of other more focused corridor studies.

Potential Action Items

- Identify data sources for key data needs;
- Work within MDOT and with partner agencies to identify opportunities to conduct a more refined evaluation of asset vulnerability (see Corridor Planning below).

5.1.2 Monitoring and Capacity Building

This study provides MDOT with a rich data set that will be useful for supporting future analyses. Given the uncertainty surrounding future projections, however, one of the clear steps that MDOT will want to take is to continue ongoing monitoring of these issues. As evidenced by the diversity of stakeholders represented on the TAC, several Michigan agencies are grappling with the implications of a changing climate. Sharing the findings from this assessment on a common state platform would be a positive step toward further collaboration on these challenges. Also, identifying common areas of interest for future planning efforts could maximize limited resource dollars for addressing climate-related challenges.

As MDOT pursues monitoring, it will be important to continue to track data. The data for the current study will be superseded by future climate projections. Given the relative lack of variability in expected future climate changes across the state, it may be sufficient for MDOT to follow the general literature, without necessarily conducting another process to downscale data to much smaller regions below the state or sub-regional level.

The data that has been provided could be useful to support risk analyses that MDOT already conducts for its assets. For example, the climate exposure information could be used in concert with the scour critical assessment conducted for bridges to help when considering future options. Further integration of the assessment risk scores into existing roadway and bridge monitoring programs could begin to institutionalize the practice of considering climate risk within existing asset management systems that lead to capital investment decisions.

Potential Action Items

- Investigate incorporating risk data into the Michigan Geographic Framework (statewide GIS framework) or otherwise provide access to current data within MDOT systems and to other partners.
- Begin monitoring roadway closure frequency and duration in high-risk areas.
- Coordinate with partner agencies to identify high-risk areas in state and local Multi-Hazard Mitigation Plans.
- Establish a climate resiliency working group to track progress and challenges of integrating climate risk with asset management.

5.1.3 Integration into the State Long Range Plan

For more long-range planning and system preservation investments, integrating climate resiliency goals into the state long range plan would be a significant first step. The long range plan is a critical document for identifying the priorities for the state, and over time shapes how Michigan invests in its infrastructure. Carefully examining how resiliency and adaptation should be considered with the agency's strategic direction will help to establish its importance. To the extent that the long range plan considers future scenarios of growth and development, it may be of value for MDOT to consider how climate change could impact that growth. Increased road closures due to extreme precipitation, for example, may have an unexpected impact of future development patterns that would be worth exploring in a long term context.

The long range plan may also be an appropriate place to begin developing a repository of long term adaptation strategies to address future challenges from extreme weather. These strategies range across the functions of the agency (from planning through design and construction and into operations and maintenance) and can help start to focus MDOT on what information it needs to make important decisions. Several state DOTs have begun to conduct a thorough review of adaptation practices, whether as part of a long range plan or separately.

Action Items

- Identify climate resiliency goals and strategies and integrate into Michigan State Long-Range Transportation Plan
- Incorporate climate risk scores for extreme heat into Road Quality Forecast System (RQFS) and Remaining Service Life (RSL) strategies. Begin monitoring performance relative to standard reconstruction and rehabilitation timeframes.

- Incorporate risk scores into Bridge Management System (BMS). Associate climate risk score for each bridge in the National Bridge Inventory, Pontis Bridge Inspection, and Structure Inventory and Appraisal reporting systems.

5.1.4 Corridor Planning

Focusing climate vulnerability assessment and adaptation activities at the corridor level is a logical next step for MDOT to further assess high-risk assets. The statewide scale at which this study was conducted makes it challenging to focus in on individual vulnerabilities. MDOT could conduct independent corridor studies or partner with regional and local agencies to examine climate vulnerability/exposure for a wider range of assets (type) and owner (local and state) but in a more focused geographic area. Members of the technical advisory committee were particularly interested in partnering with MDOT on these types of efforts.

The delineation of future study corridors can be done with any number of criteria. The study team developed a sample set of criteria that reflect the results of the assessment risk analysis and are consistent with Corridors of National/International or Statewide Significance delineated in the 2035 State Long-Range Transportation Plan. In particular, these corridors may undergo more near-term planning analysis for purposes beyond investigation of climate impacts. The following criteria were used to identify potential corridors for future study consideration by MDOT:

- Extreme precipitation risk score above 85. Extreme precipitation risk was used because the impacts are expected to be greater than those for extreme heat;

- Designated as a corridor of highest significance (specifically, corridors of national/ international or statewide significance) in the 2035 State Long-Range Transportation Plan;

- Low redundancy/lack of adequate alternate routes; and

- High truck traffic volumes/important freight corridor.

In addition to these factors, other additional corridor features – such as links to important activity centers, or roadway characteristics such as subgrade sections – were also noted. For several reasons, most of the corridors focused on the southern part of Michigan, so several corridors were selected from the Upper Peninsula and the Northern Lower Peninsula. While these corridors have lower risk scores than many corridors in the more populated southern Lower Peninsula, they have higher risk scores relative to other roadways in their respective regions. In total, 10 corridors were identified (Figure 5.2 and Table 5.1).

Figure 5.1 Corridors Recommended for Further Risk Analysis

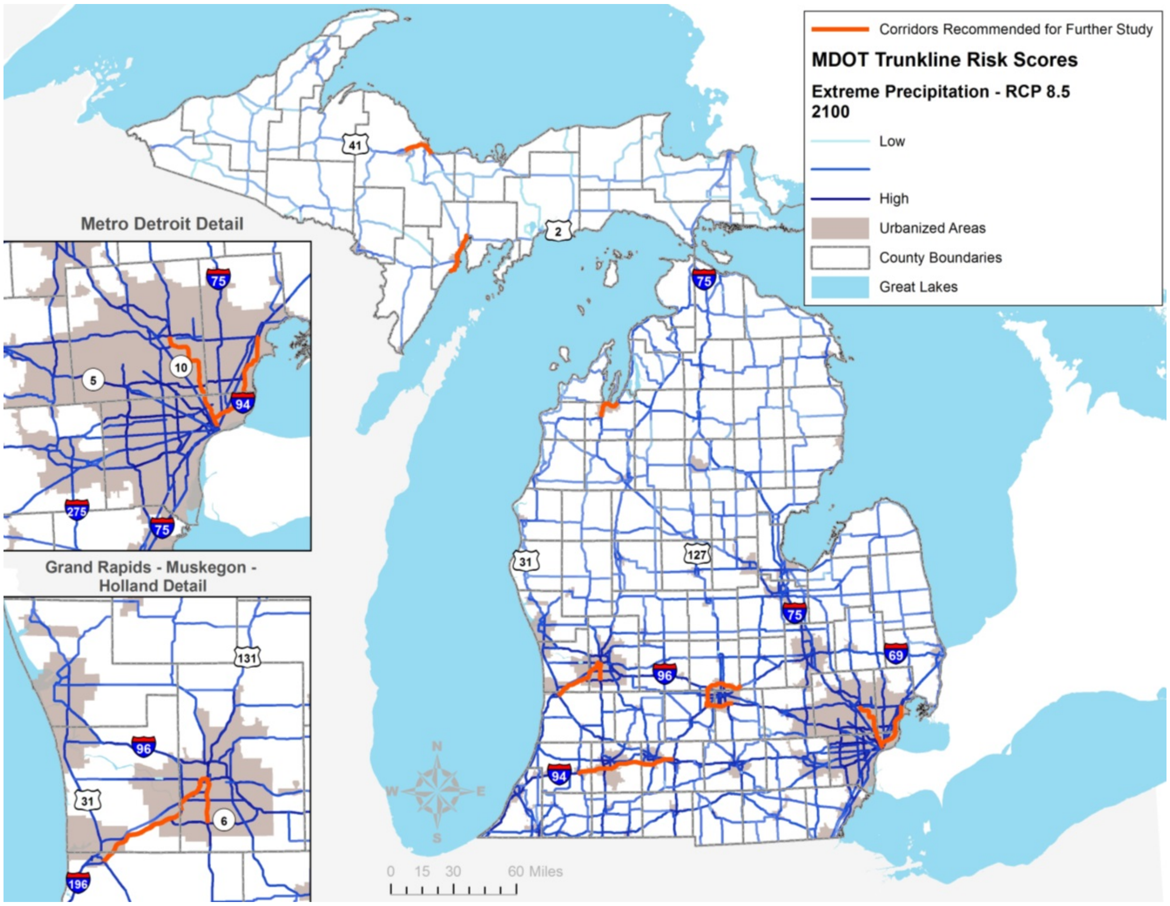


Table 5.2 Corridors Recommended for More Detailed Analysis

Area	Corridor	Criteria
Detroit	I-94 from M- 59 to I-75	• Several subgrade sections • Lacks good alternate routes for transporting freight to and from the Port Huron border crossing • Connects with Selfridge Air National Guard Base • Corridor of national/international significance • High truck traffic volumes
	I-75 from M- 59 in Pontiac to downtown Detroit	• Corridor of national/international significance • High truck traffic volumes • Many subgrade sections
Grand Rapids	U.S. 131 Between M- 6 and I-196	• Portion of corridor features the highest risk score in the State • Corridor of statewide significance • High truck traffic volumes
	I-196 from I-96 in Grand Rapids to Holland	• Corridor of national/international significance
Kalamazoo/ Battle Creek	I-94, Paw Paw to I-69 (includes Kalamazoo and Battle Creek)	• Corridor of national/international significance
Lansing	I-69 in Lansing area, from Lansing Road to Woodbury Road:	• Corridor of national/international significance
	I-96 in Lansing area, from I-69 to Okemos Road:	• Corridor of national/international significance
Marquette	U.S. 41 from M- 28 to M-28B	• Corridor of statewide significance • Risk Score of 45 • Few alternate routes
Escanaba	M- 35 from U.S. 41/U.S. 2 split in Rapid River to Ford River Bridge	• Corridor of national/international significance • Risk Score of 44 • Few alternate routes
Traverse City	U.S. 31 from M- 72 in Acme to M- 37/U.S. 31 split at Beitner Road	• Corridor of statewide significance • Risk Score of 59 • Few adequate alternate routes • High truck traffic volumes

5.1.5 Benefit Cost Analysis

Climate adjusted benefit cost analyses are useful following a risk adjusted assessment of an asset's design life, variability of climate stressor and overall risk to the facility. These assessments are becoming common practice among transportation agencies prior to planning, design and operations and maintenance decision-making. These analyses can be structured in a number of ways, but should include multiple scenarios given the variability of the climatological impact, including:

- Base condition – Following typical procedures, applying historical records as part of design practice,
- High-value existing data – applying the maximum value from within the uncertainty limits for calculated design variables,
- Increased design year value – for example, applying a 200-year storm value instead of a 100-year storm value; and
- Factored future values – based on 24-hour precipitation values from applied climate models; could include multiple model/emissions scenarios.

Each of these scenarios could be tested to determine possible design responses, including:

- What is the potential cumulative loss of functioning of damage over the lifetime of the asset (infrastructure damage, economic loss, etc.)?
- If the potential costs are high, should the facility be designed to a higher standard as a matter of course?
- What s the difference in cost associated with adaptation strategies added to the design to ensure system resiliency for each scenario?
- What are the incremental benefits of associated with adaptive design, and what are the costs avoided?

NCHRP Report 750, Volume 2, *Climate Change, Extreme Weather Events, and the Highway System* is a useful resource to explore for additional guidance on conducting climate adjusted benefit cost analysis.

Action Items

- Work with local and regional partners to conduct more in depth analysis in the above corridors.
- Develop methodologies to incorporate climate-adjusted benefit cost analysis to support investment decision making in these corridors.

5.2 Design and Construction

Changing weather patterns could have a significant impact on the choices of materials and construction methods used. Michigan relies on design standards developed by the states through the American Association of State Highway and Transportation Officials (AASHTO). These standards vary by climate region, in particular by the varying extent of freeze thaw cycles that are experienced in different parts of the country, but other factors are considered as well. At a minimum, a changing climate may make it necessary for Michigan (and other states) to adjust its materials specifications to reflect changing weather patterns.

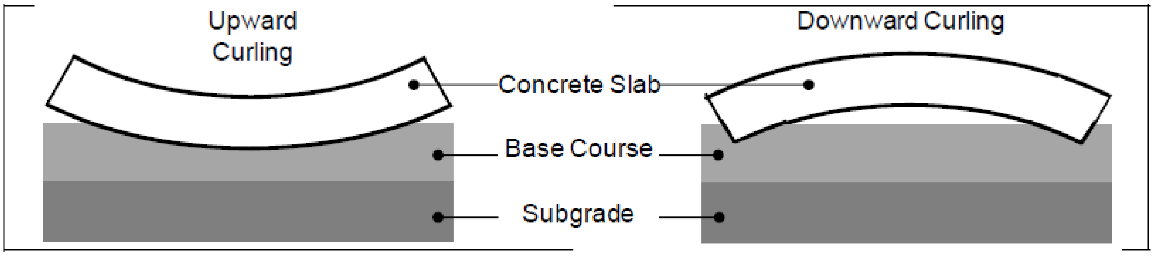
Pavement Materials

MDOT performs lifecycle cost analysis on all pavement projects expected to cost in excess of a million dollars. As part of that process, several factors are considered with respect to long term maintenance costs. Based on Michigan's Equivalent Uniform Annual Cost formula, cost over the life of the asphalt (bituminous) or concrete pavement option is calculated. The formula includes the cost of the current project, user delay costs, future maintenance costs, and the expected life of repairs. Michigan has a higher proportion of concrete pavements than many states. Over 90 percent of the nation's roadways are asphalt while in Michigan, only 84 percent are asphalt. This mix slightly modifies Michigan's position with respect to long term and life cycle climate influenced impacts.

Asphalt and concrete pavements perform differently in extreme temperatures. Among the most commonly cited infrastructure impacts related to climate conditions and extreme weather events are buckling, washouts, and other hydraulic related failures. Both asphalt and concrete pavements can show signs of buckling due to temperature changes to base materials. Concrete pavements buckle when temperature changes cause material expansion. Asphalt suffers "blowouts" as higher moisture penetration results in rapid expansion when heated. Rapid pavement deterioration can cause driving hazards and are challenging to predict, regardless of pavement surface material.

While a wide body of literature is available on the long term sustainability of concrete (rigid) and asphalt (flexible) based pavements few studies address the long term viability of pavements with respect to changes in climate. A 2012 Australian study suggested that the likelihood of cracking in concrete increases significantly with changes in average temperature gradients causing downward curling of concrete slabs (Figure 5.2). Temperature extremes have been consistently cited as a reason for buckling, but the gradual temperature increases and downward curling with longer term temperature increases has not been modeled elsewhere. The study held that the impacts of thermal-expansive stresses are severe under climate change projections. While the laboratory results did confirm the findings, the study has not been field validated (Chai and van Staden, 2012). The authors, however, did not find that curling and small cracking of concrete was more costly or severe than rutting and other asphalt pavement deficiencies due to temperature (spalling, thermal cracking, or softening).

Figure 5.2 Temperature variations cause curling and thermal-expansion stresses within concrete



Source: Chai, Gary and van Staden, Rudi. Impact of Climate Related Changes in Temperature on Concrete Pavement: A Finite Element Study, presented at 25th ARRB Conference – Shaping the future: Linking policy, research and outcomes, Perth, Australia 2012.

Action Items

- Conduct research on how climate change and extreme weather may impact the benefits and costs of various material specifications used by MDOT.
- Over time, identify design modifications or thresholds (or other adaptation strategies) to reduce long term vulnerability

5.3 Operations and Maintenance

Operation, maintenance, and construction practices will require close attention, and perhaps significant adjustment under future climate projections. Longer summers and warmer spring and summer seasons may provide an opportunity to extend construction and repair timeframes; however, extreme heat events may have the opposite effect, by limiting construction days due to concerns for worker safety.

Winter weather maintenance expenditures, including keeping roadways safe and passable, as well as budgets for postseason repairs, will need to be monitored due to the expected increase in winter precipitation. While freeze thaw cycles are expected to decline in the long run, they will continue to pose maintenance challenges in the short run and some areas (such as the Upper Peninsula) could see increases in freeze thaw conditions due to warmer winters. Freeze thaw cycles were among the most challenging climate stressor to predict, because they depend not just on individual months or days, but the sequence of freeze and thaw events across multiple days and weeks.

Increased precipitation overall will create challenges by increasing or exacerbating road closures. The recent flooding events in Detroit caused significant road closures, and these can reasonably be expected to increase in number and duration in the future, potentially by a significant amount. MDOT and its partners in state and local governments may need to determine acceptable tolerance for road closures.

Similarly, the failure of pumping and stormwater systems should be monitored. Recent extreme precipitation in the Detroit Metro area and subsequent flooding of the freeway system calls attention to the challenges of pumping water from depressed freeways. Furthermore, the five climate models selected for this study indicate that the quantity constituting the 50 year rainfall event in Detroit—currently 3.43 inches in a 24-hour period—will increase to between 3.6 to 4.31 inches in 2050, and to between 3.77 to 5.54 inches in 2100. Given the lack of adaptive capacity in existing urban infrastructure, pumping systems are an area where short term capital investment may be needed, especially since they were designed to handle 50-year extreme precipitation events for the present climate. However, Michigan's generally low elevation and broad flood plains make it challenging to solve this particular issue. While pumps can be replaced so they are less prone to failure and expanded to handle a greater capacity, there are significant stormwater capacity limits that limit MDOT's ability to take action.

Action Items

- Begin tracking extreme weather-related disruptions to seasonal construction days. Adjust guidelines for construction practices.
- Continue tracking extreme winter weather materials expenditures and maintenance costs.
- Evaluate the economic impacts of roadway closures in various parts of the state (potentially on the corridors defined above) and establish thresholds for acceptable closure levels for various precipitation scenarios.
- Conduct a more in-depth evaluation of the use of pump infrastructure to determine if additional capacity can be generated or if additional investment is feasible.

5.4 Summary of Lessons Learned

The study team identified several lessons learned throughout the course of this pilot study. These include both successes and challenges requiring future investigation, and are summarized here:

- **Challenge of picking thresholds**. The current study used a continuous range of exposure to climate risk, but explored thresholds to better capture the significance of the risk. While the MDOT working group helped establish some concepts, it was challenging to define precise thresholds that identified significant risk. Additional work on this, either for Michigan or more generally, would be helpful to help establish risk tolerances that could be used in planning and design.

- **The use of multiple models helped ensure that uncertainty was appropriately addressed**. This study made use of 5 climate models that captured the range of future climate impacts in Michigan. The findings for future extreme precipitation events illustrate the benefit of this approach. For some scenarios (analysis year and emissions), changes in precipitation ranged from very little change to over 60 percent increase. If a single model was used, it might have provided false precision to these estimates. The level of uncertainty is an important factor to consider in a risk analysis. The study team recognizes this approach can be frustrating for decision makers looking for definitive information to support making specific decisions, but the uncertainty of future projections is a critical element. The study team used box plots and similar information to convey the uncertainty of the estimates. Continuing to identify opportunities and methods for presenting and using uncertainty in decision making would be valuable for future vulnerability and risk assessments.

- **Limited value of downscaling at a statewide scale**. However, one area where the climate modeling was less useful for Michigan was in disaggregating the data from the climate models into more detailed climate station specific scores. While some of the climate variables did vary from north to south, most of the variation was across the climate models. For monitoring purposes, it may be sufficient for MDOT and other state agencies to consider the scale from the climate models and potentially use more models to have a better understanding of the certainty of estimates. Data from the National Climate Assessment, which was published during the course of this study, may also be a sufficient resource for assessing high level impacts to transportation assets at a statewide scale.

- **Elevation and floodplain data were significant needs**. The relative lack of variation of climate impacts across Michigan particularly highlighted the need for more robust elevation and floodplain data as elements of the vulnerability analysis. At a statewide scale, it was challenging to complete a full vulnerability assessment, and instead the analysis focused primarily on exposure. A contiguous National Flood Hazard Layer (NFHL) for the state of

Michigan, or digitized Flood Insurance Rate Maps (FIRM) for areas identified as potential high risk through this analysis, combined with high resolution elevation data (such as LiDAR) would allow for a more thorough assessment of asset sensitivity and adaptive capacity, especially at a more focused level. These data sets are widely available in coastal areas, but were not readily available for this study. As an example, the Saginaw case study was assigned a high-risk score to an interstate bridge that crossed a major river, though the bridge had been recently reconstructed and elevated. Better quality topographic and structural elevation data specific to the asset would also help refine the risk scores. Future studies at a corridor or subarea level would do well to focus in on these data sources to best understand sensitivity of the assets.

- **Leverage existing data and information**. The study team made use of MDOTs scour critical bridge inventory and analysis framework for determining criticality, which in turn informed the overall risk score. Because this approach is consistent with existing practice, MDOT can more readily integrate these findings into other planning and investment analysis efforts.

A APPENDIX A – TRANSPORTATION DATA GAPS

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B APPENDIX B – CLIMATE ANALYSIS

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C APPENDIX C – RISK ASSESSMENT MAPS

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