CALTRANS CLIMATE CHANGE VULNERABILITY ASSESSMENTS

June 2019

District 8
Technical Report

CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

ADAP	Adaptation Decision-Making Assessment Process
CalFire	California Department of Forestry and Fire Protection
Caltrans	California Department of Transportation
CAP	Climate Action Plan/Planning
CCC	California Coastal Commission
CEC	California Energy Commission
CGS	California Geological Survey
DWR	California Department of Water Resources
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GCM	Global Climate Model
GHG	Greenhouse Gas
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LOCA	Localized Constructed Analogues
RCP	Representative Concentration Pathway
Scripps	The Scripps Institution of Oceanography
SHS	State Highway System
SRES	Special Report Emissions Scenarios
USFS	US Forest Service
VHT	Vehicle Hours Traveled

This page intentionally left blank.

1. INTRODUCTION

The following report was developed for the California Department of Transportation (Caltrans) and summarizes a vulnerability assessment conducted for the portion of State Highway System (SHS) in Caltrans District 8. Though there are multiple definitions of vulnerability, this assessment specifically considers vulnerabilities from climate change.

Climate change and extreme weather events have received increasing attention worldwide as one of the greatest challenges facing modern society. Many state agencies—such as the California Coastal Commission (CCC), the California Energy Commission (CEC), and the California Department of Water Resources (DWR)—have developed approaches for understanding and assessing the potential impacts of a changing climate on California's natural resources and built environment. State agencies are invested in defining the implications of climate change and many of California's academic institutions are engaged in developing resources for decision-makers. Caltrans initiated the current study to better understand the vulnerability of California's State Highway System and other Caltrans assets to future changes in climate. The study has three objectives:

- Understand the types of weather-related and longer-term climate change events that will likely occur with greater frequency and intensity in future years,
- Conduct a vulnerability assessment to determine those Caltrans assets vulnerable to various climate-influenced natural hazards, and
- Develop a method to prioritize candidate projects for actions that are responsive to climate change concerns, when financial resources become available.

The current study focuses on the 12 Caltrans districts, each facing its own set of challenges regarding future climate conditions and potential weather-related disruptions. The District 8 report is one of 12 district reports that are in various stages of development.

1.1. Purpose of Report

The *District 8 Technical Report* is one of two documents developed to describe the work completed for the District 8 vulnerability assessment, the other being the *District 8 Summary Report*. The *Summary Report* provides a high-level overview on methodology, the potential implications of climate change to Caltrans assets and how climate data can be applied in decision-making. It is intended to orient non-technical readers on how climate change may affect the State Highway System in District 8.

This *Technical Report* is intended to provide a more in-depth discussion, primarily for District 8 staff. It provides background on the methodology used to develop material for both reports and general information on how to replicate those methods, if desired. The report is divided into sections by climate stressor (e.g. wildfire, temperature, precipitation) and each section presents:

- How that climate stressor is changing,
- The data used to assess SHS vulnerabilities from that stressor,
- The methodology for how the data was developed,
- Maps of the portion of district SHS exposed to that stressor,

- And where applicable, mileage of exposed SHS.

Finally, this *Technical Report* outlines a recommended framework for prioritizing a list of projects that might be considered by Caltrans in the future. This framework was developed based on research of other prioritization frameworks used by transportation agencies and alternative frameworks developed to guide decision-making given climate change.

All data used in the development of the District 8 Technical and Summary Reports was collected into a single database by the project study team, which is made up of the WSP staff who prepared this assessment and report. Caltrans will be able to use this data in future mapping efforts and analyses and it is expected to be a valuable resource for ongoing resiliency planning efforts. The contents of the District 8 database are also available to the public in an online interactive mapping tool.[1]

1.2. District 8 Characteristics

Caltrans District 8 consists of Riverside and San Bernardino Counties, which include a total of 52 incorporated cities. It is the largest Caltrans district, covering approximately 28,650 square miles. District 8 contains 28 state routes, four interstates and two U.S. routes totaling 7,200 lane-miles. Many of the district's major state highways are severely congested during peak periods due to the high number of commuters to and from Los Angeles, Orange, and San Diego Counties. In addition to weekday congestion during morning and afternoon peak hours, Interstate 10 is heavily used for long distance recreational and goods movement to Arizona and beyond—as is Interstate 15 to Nevada and beyond. Interstate 215 is another major goods movement corridor and is heavily used during commute peak hours. State routes 91 and 210 are heavily used for commuter and recreational destination travel, and State Route 58 and Interstate 40 carry substantial volumes of goods movement traffic and intraregional and interregional travelers. Interstate 15 sees heavy use from tourism to and from Nevada in the north and the transportation of commodities from Mexico and San Diego in the south. This congestion is expected to increase due to population and employment growth. The Southern California Association of Governments (SCAG) found that the regional transportation plan for this area does not meet the plan's minimum LOS "D" operating condition, nor the district's desired system-wide route concept on much of the urban highway system, and some very significant portions of rural interstates.

High winds are prevalent in sections of all four of the interstates and are of particular concern in the Palm Springs area of Interstate 10 and the Cajon Pass area of Interstate 15, from which high-profile vehicles must be diverted when gusts reach 55 miles per hour. The Santa Ana winds are especially strong in autumn in San Bernardino where they funnel through Cajon Pass and increase wildfire risk in the foothills. Portions of District 8 get much colder than other regions in Southern California, and in the

[1] "Vulnerability Assessment," Caltrans, last accessed May 9, 2019, http://www.dot.ca.gov/transplanning/ocp/vulnerability-assessment.html

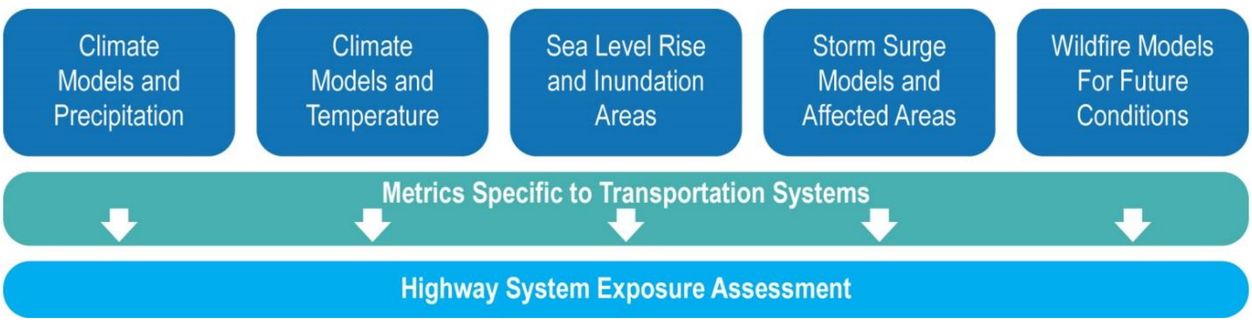
winter, the district needs to clear the highways of snow to keep the San Bernardino and San Gabriel Mountains open for recreation-focused travel as well as regular local and regional travel. Additionally, the portion of the district located in desert regions is subject to irregular, but sometimes intense, rainfall which then courses through dry washes of varying widths and depths.

2. POTENTIAL EFFECTS FROM CLIMATE CHANGE ON THE STATE HIGHWAY SYSTEM IN DISTRICT 8

Climate and extreme weather conditions in District 8 are changing as greenhouse gas (GHG) emissions lead to higher temperatures. These changing conditions are anticipated to affect the State Highway System in District 8 and other Caltrans assets. These impacts may appear in a variety of ways and may increase district infrastructure's exposure to environmental factors that exceed the original design considerations. The project study team considered a range of climate stressors and how they align with Caltrans design criteria/other metrics specific to transportation systems.

Figure 1 illustrates the general process for deciding which metrics should be included in the overall SHS vulnerability assessment. First, Caltrans and the project study team considered which climate stressors affect transportation systems. Then, Caltrans and the project study team decided on a relevant metric that the climate stressor data could inform. For example, precipitation data was formatted to show the 100-year storm depth, as the 100-year storm is a criterion used in the design of Caltrans assets.

FIGURE 1: CONSIDERATIONS FOR THE STATE HIGHWAY ASSESSMENT



Extreme weather events already disrupt and damage District 8 infrastructure. The following examples include issues and events that Caltrans District 8 has addressed in the past, which may become more prevalent as climatic changes occur and extreme weather becomes more frequent.

- **Temperature –** District 8 includes a broad geography with urban areas, the Mojave Desert which includes Joshua Tree National Park and Death Valley, and part of the San Gabriel Mountains and all of the San Bernardino Mountains. Temperatures are expected to rise in these areas in the future and effect each region differently. The mountainous regions may face a higher risk of tree mortality due to drought and heat, while desert vegetation could also be negatively affected. Both effects could increase fire potential in District 8. These types of impacts may become more frequent as temperatures rise, droughts occur, and vegetation dries out.

- **Precipitation** – In December of 2010, multiple subtropical storms hit District 8. These storms lasted a week and delivered between 7 and 17 inches of rain, depending on location. These sudden and extreme rain events exceeded the capacities of multiple District 8 culverts, including one at Willow Creek Road and others along State Route 18. Overflow from the culverts flooded nearby roadways, washed out berms and slopes, and undermined roadbeds. See Figure 3 and Figure 2 for photos of the event. District 8 infrastructure experienced similar impacts again in 2017 when large portions of the state suffered from flooding, erosion, and washouts from extreme weather. As the climate changes, heavy and extreme precipitation is expected to increase in California and these types of events may become more commonplace in District 8.

FIGURE 3: CULVERT OVERFLOW ON WILLOW CREEK ROAD

Wildfire – As temperatures rise and precipitation patterns become more unpredictable, wildfire risk is expected to increase. Recent studies have found that the droughts of the last 15 years were "more intense than early- to mid-20th century droughts, with greater temperature and precipitation extremes," which could contribute to more severe fires and widespread tree mortality in drought-affected areas.[2] There were many severe wildfires following the drought from 2011 to 2017, one of the most notable being the 2016 Blue Cut Fire in Cajon Pass. The Blue Cut Fire jumped I-15 in District 8 and destroyed 105 homes, 213 other buildings, multiple vehicles, and pieces of highway infrastructure. The fire burned 36,274 acres off I-15 and Highway 138 north of San Bernardino before it was contained. Also in 2017, a brush fire on Highway 91 in Riverside County damaged the side slope, landscape area, and the metal beam guard rail.

FIGURE 4: SEMI-TRUCK BURNED DURING THE BLUE CUT WILDFIRE

FIGURE 5: HIGHWAY INFRASTRUCTURE BURNED DURING THE BLUE CUT WILDFIRE

- **Combined Effects** – When extreme weather events follow one another, the impacts can become even more severe. For example, a wildfire following a drought can be more severe and widespread than if it happened during a normal year. These types of combined effects can

[2] Joseph Crockett, Leroy Westerling., "Greater Temperature and Precipitation Extremes Intensify Western Us Droughts, Wildfire Severity, and Sierra Nevada Tree Mortality," Journal of Climate 31(1):341-354. doi:10.1175/JCLI-D-17-0254.1 (2018), https://cloudfront.escholarship.org/dist/prd/content/qt3t39d8jq/qt3t39d8jq.pdf?t=osfbdf&v=lg

sometimes be predicted and prepared for. If a wildfire burns a slope, Caltrans can take steps to stabilize that slope in preparation for the rainy season and thereby reducing the risk of landslides. If these events cannot be prevented, Caltrans will have to respond afterwards. The following provides one example of an event caused by multiple factors in District 8 and the response.

- **Slope Degradation** – In 2017, winter storms caused serious damage across the Caltrans State Highway System. In District 8, these heavy rains led to increased runoff on State Route 38 (SR-38). This additional flow led to the collapse of a retaining system and ongoing slope degradation in a site that was already steep and unstable. See Figure 6 for photos of the event on SR-38. The site profile combined with heavy, concentrated roadway runoff destabilized the site, which was restored using an embankment hinge.

FIGURE 6: SLOPE DEGRADATION ON SR-38

3. ASSESSMENT APPROACH

3.1. General Description of Approach and Review

The development of this report required extensive coordination with Caltrans District 8, and included coordinating on previous work sponsored and completed by District 8 staff to identify available data, findings, and lessons learned. The project study team also discussed vulnerability assessment methodology and deliverables with District 8 staff, and coordinated with them to collect relevant District 8 photos and background information for this report. Finally, District 8 were key to reviewing the material presented in this report.

The methods used as part of the vulnerability assessment shown in the following pages also included coordination with California organizations responsible for climate model and data development. These agencies and research institutions will be discussed in more detail in the following pages (see Section 3.2.2) and in the respective sections on each stressor.

3.2. State of the Practice in California

California has been on the forefront of climate change policy, planning, and research across the nation. State officials have been instrumental in developing and implementing policies that foster effective greenhouse gas mitigation strategies and the consideration of climate change in state decision-making. California agencies have also been pivotal in creating climate change data sets that can be used to consider regional impacts across the state. At a more local level, efforts to plan for and adapt to climate change are underway in communities across California. These practices are key to the development of climate change vulnerability assessments in California and were found to be very helpful in the development of the District 8 report (some of these reports are described later). The sections below provide some background on the current state-of-the-practice in adaptation planning and how specific analysis methods were considered/applied in the District 8 vulnerability assessment.

3.2.1. Policies

Various policies implemented at the state level have directly addressed not only GHG mitigation, but climate adaptation planning. These policies require state agencies to consider the effects of climate in their investment and design decisions, among other considerations. State adaptation policies that are relevant to Caltrans include:

- **Assembly Bill 32** (2006) or the "California Global Warming Solution Act" was marked as being the first California law to require a reduction in emitted GHGs. The law was the first of its kind in the country and set the stage for further policy in the future.[3]
- **Executive Order S-13-08** (2008) directs state agencies to plan for sea level rise (SLR) and climate impacts through the coordination of the state Climate Adaptation Strategy.[4]
- **Executive Order B-30-15** (2015) requires the consideration of climate change in all state investment decisions through: full life cycle cost accounting, the prioritization of

[3] "Assembly Bill 32 Overview," California Air Resources Board, last modified August 5, 2014, https://www.arb.ca.gov/cc/ab32/ab32.htm
[4] "California Executive Order S-13-08 Requiring State Adaptation Strategy," Adaptation Clearinghouse, last accessed April 30, 2019, https://www.adaptationclearinghouse.org/resources/california-executive-order-s-13-08-requiring-state-adaptation-strategy.html

adaptation actions that also mitigate greenhouse gases, the consideration of the state's most vulnerable populations, the prioritization of natural infrastructure solutions, and the use of flexible approaches where possible.[5]

- **Assembly Bill 1482** (2015) requires all state agencies and departments to prepare for climate change impacts through (among others) continued collection of climate data, considerations of climate in state investments, and the promotion of reliable transportation strategies.[6]
- **Senate Bill 246** (2015) establishes the Integrated Climate Adaptation and Resiliency Program to coordinate with regional and local efforts with state adaptation strategies.[7]
- **Assembly Bill 2800** (2016) requires that state agencies account for climate impacts during planning, design, building, operations, maintenance, and investments in infrastructure. It also requires the formation of a Climate-Safe Infrastructure Working Group represented by engineers with relevant experience from multiple state agencies, including the Department of Transportation.[8]

These policies are among the factors state agencies consider when addressing climate change. Conducting an assessment such as this one for District 8 is a key step towards preserving Caltrans infrastructure against future extreme weather conditions and addressing the requirements of the relevant state policies above, such as Executive Order B-30-15, Assembly Bill 1482, and Assembly Bill 2800. Other policies, such as Executive Order S-13-08, stimulate the creation of climate data that can be used by state agencies in their own adaptation planning efforts. It is important for Caltrans staff to be aware of the policy requirements defining climate change response and how this assessment may be used to indicate compliance, where applicable.

One of the most important climate adaptation policies out of those listed above is Executive Order B-30-15. Guidance specific to the Executive Order and how state agencies can begin to implement was released in 2017, titled *Planning and Investing for a Resilient California*. This guidance will help state agencies develop methodologies in completing vulnerability assessments specific to their focus areas and in making adaptive planning decisions. *Planning and Investing for a Resilient California* created a framework to be followed by other state agencies, which is important in communicating the effects of climate change consistently across agencies.[9]

3.2.2. Research

California has been on the forefront of climate change research nationally and internationally. For example, Executive Order S-03-05, directs that state agencies develop and regularly update guidance on climate change. These research efforts are titled the California Climate Change Assessments, which is in its fourth edition (Fourth Climate Change Assessment). To understand the research and datasets coming

---

[5] "Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America," Office of Governor Edmund Brown, last modified April 29, 2015, https://www.ca.gov/archive/gov39/2015/04/29/news18938/

[6] "Assembly Bill No. 1482," California Legislative Information, October 8, 2015, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1482

[7] "Senate Bill No.246," California Legislative Information, October 8, 2015, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB246

[8] "Assembly Bill No. 2800," California Legislative Information, September 24. 2016, http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2800

[9] Governor's Office of Planning and Research, "Planning and Investing for a Resilient California: a Guidebook for State Agencies," March 13th, 2018, http://opr.ca.gov/planning/icarp/resilient-ca.html

out of the Fourth Climate Change Assessment, which are utilized in this District 8 vulnerability assessment, some background is needed on Global Climate Models and emissions scenarios.

Global Climate Models (GCMs)

GCMs have been developed worldwide by many academic or research institutions to represent the physical processes that interact to cause climate change, and to project future changes to GHG emission levels.[10] These models are run to reflect the different estimates of GHG emissions or atmospheric concentrations of these gases, which are summarized for use by the Intergovernmental Panel on Climate Change (IPCC).

The IPCC is the leading international body recognized for its work in quantifying the potential effects of climate change and its membership is made up of thousands of scientists from 195 countries. The IPCC periodically releases Assessment Reports (currently in its 5th iteration), which summarize the latest research on a broad range of topics relating to climate change. The IPCC updates research on GHG emissions, identifies scenarios that reflect research on emissions generation, and estimates how those emissions may change given international policies. The IPCC also summarizes scenarios of atmospheric concentrations of GHG emissions to the end of the century.

There are dozens of climate models worldwide, but there are a set of GCMs that have been identified for use in California, as outlined in the California Fourth Climate Change Assessment section.

Emissions Scenarios

There are two commonly cited sets of emissions data that are used by the IPCC:

1. The Special Report Emissions Scenarios (SRES)
2. The Representative Concentration Pathways (RCPs)

RCPs represent the most recent generation of GHG scenarios produced by the IPCC and are used in this report. These scenarios use three main metrics: radiative forcing, emission rates, and emission concentrations.[11] Four RCPs were developed to reflect assumptions for emissions growth, and the resulting concentrations of GHG in the atmosphere. The RCPs developed are applied in GCMs to identify projected future conditions and enable a comparison of one against another. Generally, the RCPs are based on assumptions for GHG emissions growth and an identified point at which they would be expected to begin declining (assuming varying reduction policies or socioeconomic conditions). The RCPs developed for this purpose include the following:

- RCP 2.6 assumes that global annual GHG emissions will peak in the next few years and then begin to decline substantially.
- RCP 4.5 assumes that global annual GHG emissions will peak around 2040 and then begin to decline.
- RCP 6.0 assumes that emissions will peak near the year 2080 and then start to decline.

[10] "What is a GCM?", Intergovernmental Panel on Climate Change, last accessed April 30, 2019, http://www.ipcc-data.org/guidelines/pages/gcm_guide.html
[11] "Representative Concentration Pathways," IPCC, last accessed April 30, 2019, http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html

- RCP 8.5 assumes that high GHG emissions will continue to the end of the century.[12]

California Fourth Climate Change Assessment

The California Fourth Climate Change Assessment was an inter-agency research and "model downscaling" effort for multiple climate stressors. The Fourth Climate Change Assessment was led by the California Energy Commission (CEC), but other contributors included agencies such as the Department of Water Resources (DWR) and the Natural Resources Agency, as well as academic institutions such as the Scripps Institution of Oceanography (Scripps) and the University of California, Merced.[13]

Model downscaling is a statistical technique that refines the results of GCMs to a regional level. The model downscaling used in the Fourth Climate Change Assessment is a technique called Localized Constructed Analogs (LOCA), which "uses past history to add improved fine scale detail to GCMs."[14] This effort was undertaken by Scripps and provides a finer resolution than is found in other techniques, enabling the assessment of changes in a more localized way.[15] Out of the 32 LOCA downscaled GCMs for California, 10 models were chosen by state agencies as being most relevant for California. This effort was led by DWR and its intent was to understand which models to use in state agency assessments and planning decisions.[16] The 10 representative GCMs for California are:

- ACCESS 1-0
- CanESM2
- CCSM4
- CESM1-BGC
- CMCC-CMS
- CNRM-CM5
- GFDL-CM3
- HadGEM2-CC
- HadGEM2-ES
- MIROC5

Data from these models are available on Cal-Adapt 2.0, California's Climate Change Research Center.[17] The Cal-Adapt 2.0 data is some of the best available data in California on climate change and, for this reason, selections of data from Cal-Adapt and the GCMs above were utilized in this study.

[12] Meinshausen, M.; et al. (November 2011), "The Rcp Greenhouse Gas Concentrations and Their Extensions From 1765 To 2300 (Open Access)", Climatic Change, 109 (1-2): 213–241

[13] "California's Fourth Climate Change Assessment," State of California website (CA.gov), last accessed June 5th, 2019, http://www.climateassessment.ca.gov/

[14] "LOCA Downscaled Climate Projections," Cal-Adapt, last accessed April 30, 2019, http://cal-adapt.org/

[15] Pierce et al.,"Statistical Downscaling Using Localized Constructed Analogs." 2014. http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-14-0082.1

[16] "LOCA Downscaled Climate Projections," Cal-Adapt, last accessed April 30, 2019, http://cal-adapt.org/

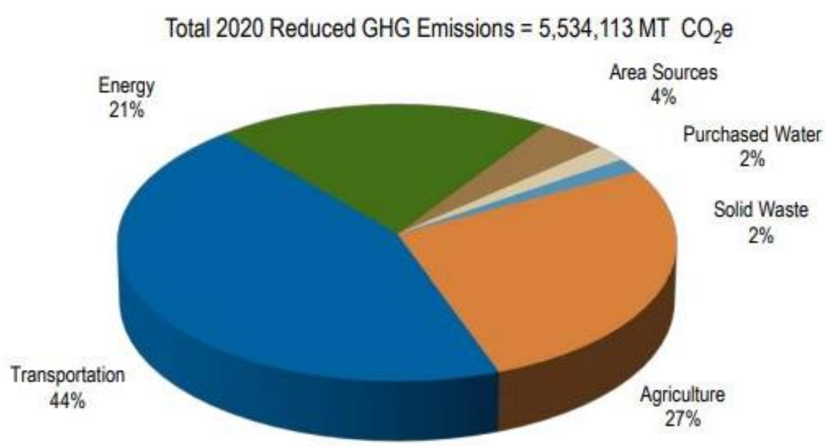
[17] For more information, visit http://cal-adapt.org/

3.3. Other District 8 Efforts to Address Climate Change

In addition to the work done by Caltrans, there are regional efforts underway in District 8 relating to climate change planning and preparedness. Both counties within the district have developed and adopted reports/plans designed to mitigate GHG emissions, reduce the impacts of climate change to local communities, and build resilience to climate change. Some examples of these efforts in District 8 include:

- **The Riverside County Climate Action Plan** – Riverside County completed a Climate Action Plan (CAP) in dated July 17, 2018 to reduce GHGs, preserve local air quality, conserve energy, and ensure that county decisions meet state legislative requirements. The CAP established a GHG emission inventory by sector and outlined measures to meet Assembly Bill 32's target of reaching 1990 GHG levels by 2020. Some of these measures include expanding low-emissions vehicle use, and implementing a residential retrofit program, solar energy financing, and waste education. By following these GHG reduction measures the county is projected to reduce emissions to 15% less than 2008 emission levels, as recommended in the AB 32 Scoping Plan. The development of this CAP coincides with Riverside County's General Plan Update. A community-wide emissions inventory is also calculated for the horizon year of 2035. The socioeconomic growth rates from the General Plan Update were used to estimate the 2035 emissions." Figure 7 shows targeted emissions by sector in 2020.[18]

FIGURE 7: REDUCED RIVERSIDE GHG EMISSIONS BY SOURCE IN 2020



- **San Bernardino County Regional Greenhouse Gas Reduction Plan** – The San Bernardino County Regional GHG Reduction Plan summarizes actions that each city in the county can take to reduce their GHG emissions and estimate local GHG emissions reduction progress. The plan helps the county assess GHG sources, streamline project approvals, evaluate strategy effectiveness and cost, maintain involvement in local GHG reduction efforts, and give cities credit for past efforts.

[18] Riverside County, "Riverside County Climate Action Plan," December 2015, https://planning.rctlma.org/CAP

The plan is useful for cities to reference within their work and incorporate into a local CAP if desired.[19]

- **Climate Change and Health Profile Reports for San Bernardino and Riverside Counties –**San Bernardino and Riverside Counties produced reports about climate change and future health impacts to county residents. Both reports include regional climate projections for temperature, heat waves, fire, precipitation, and snow pack, and describe how these changes in climate could impact public health. Climatic changes can cause a range of impacts to water and air quality, weather, and the local environment that can subsequently lead to disease, injuries, malnutrition, and mental health effects in humans. These impacts may be disproportionately felt by vulnerable populations such as the very young or elderly, disabled, low income, or those with other health conditions. To identify the size of these population groups who are at the highest risk, both county reports provide local population demographic profiles. Some of these statistics are summarized below:

    - 49% of San Bernardino and 47% of Riverside residents surveyed reported multiple chronic health conditions, as opposed to 44% statewide.
    - 16% of San Bernardino residents surveyed were diagnosed with asthma, with the highest proportion affected being African American. This compares to 13% in Riverside and 14% statewide.
    - Both counties reported that 11% of the respective populations are living with a disability.
    - 7% of San Bernardino and 9% of Riverside residents work outdoors.
    - 15% of San Bernardino and 13% in Riverside live below the poverty line.

  Each report suggests ways that the counties can act to protect these people and the rest of the public against the projected climate-related health impacts. Some of these suggestions can be enacted in the near-term, like starting a public outreach campaign, improving heat warning systems, and further research on the nexus between climate change and health. Other suggestions are long-term goals, such as developing resiliency funding opportunities and reducing urban heat islands. [20], [21]

3.4. General Methodology

The adaptation planning methodology varies from stressor to stressor, given that each uses a different set of models, emissions scenarios, and assumptions, leading to data and information on which to develop an understanding of potential future climate conditions. The specific methods employed are

---

[19] San Bernardino Associated Governments, "San Bernardino County Regional Greenhouse Gas Reduction Plan," March 2014, http://www.gosbcta.com/plans-projects/plans/greenhouse-gas/SBC-RegionalGreenHouseGasReduction-Final.pdf

[20] Neil Maizlish, Dorette English, Jacqueline Chan, Kathy Dervin, Paul English, "Climate Change and Health Profile Report: San Bernardino County," Office of Health Equity, California Department of Public Health, 2017, https://www.cdph.ca.gov/Programs/OHE/CDPH%20Document%20Library/CHPRs/CHPR071SanBernardino_County2-23-17.pdf

[21] Neil Maizlish, Dorette English, Jacqueline Chan, Kathy Dervin, Paul English, "Climate Change and Health Profile Report: Riverside County," Office of Health Equity, California Department of Public Health, February 2017, https://www.cdph.ca.gov/Programs/OHE/CDPH%20Document%20Library/CHPRs/CHPR065Riverside__County2-23-17.pdf

further defined in each stressor section; however, there are some general practices that apply across all analysis approaches.

3.4.1. Time Periods

It is helpful to present climate projections in a way that allows for consistent comparison between analysis periods for different stressors. For this study, those analysis periods have been defined as the beginning, middle, and end of century, represented by the out-years 2025, 2055, and 2085, respectively. These years are chosen because some statistically derived climate metrics used in this report (e.g. the 100-year precipitation event) are typically calculated over 30-year time periods centered on the year of interest. Because currently available climate projections are only available through the end of the century, the most distant 30-year window runs from 2070 to 2099. 2085 is the center point of this time range and the last year in which statistically derived projections can defensibly be made. The 2025 and 2055 out-years follow the same logic, but applied to each of the prior 30-year periods (2010 to 2039 and 2040 to 2069, respectively).

3.4.2. Geographic Information Systems (GIS) and Geospatial Data

Developing an understanding of Caltrans assets exposed to sea level rise, storm surge, and projected changes in temperature, precipitation, and wildfire required complex geospatial analyses. The geospatial analyses were performed using ESRI geographic information systems (GIS) software. The general approach for each stressor's geospatial analysis went as follows:

Obtain/conduct stressor mapping: The first step in each GIS analysis was to obtain or create maps showing the presence and/or value of a given hazard at various future time periods, under different climate scenarios. For example, extreme temperature maps were created for temperature metrics important to pavement binder grade specifications; maps of extreme (100-year) precipitation depths were developed to show changes in rainfall; burn counts were compiled to produce maps indicating future wildfire frequency; and sea level rise, storm surge, and cliff retreat maps were made to understand the impacts of future tidal flooding and erosion.

Determine critical stressor thresholds: Some stressors, namely temperature, precipitation and wildfire, vary in intensity across the landscape. In many locations, the future change in these stressors is not projected to be high enough to warrant special concern, whereas other areas may see a large increase in hazard risk. To highlight the areas most affected by climate change, the geospatial analyses for these stressors defined the critical thresholds for which the value of (or the change in value of) a stressor would be a concern to Caltrans. For example, the wildfire geospatial analysis involved several steps to indicate which areas are considered to have a moderate, high, and very high fire exposure based on the projected frequency of wildfire.

Overlay the stressor layers with Caltrans State Highway System to determine exposure: Once high stressor areas had been mapped, the next general step in the geospatial analyses was to overlay the Caltrans State Highway System centerlines with the stressor data to identify the segments of roadway most exposed to each stressor.

Summarize the miles of roadway affected: The final step in the geospatial analyses involved running the segments of roadway exposed to a stressor through Caltrans' linear referencing system. This step was performed by Caltrans, and provides an output GIS file indicating the centerline miles of roadway affected by a given stressor. Using GIS, this data can then be summarized in many ways (e.g. by district, county, municipality, route number, or some combination thereof) to provide useful statistics to Caltrans planners.

Upon completion of the geospatial analyses, GIS data for each step was saved to a database that was supplied to Caltrans after the study was completed. Limited metadata on each dataset was also provided in the form of an Excel table that described each dataset and its characteristics. This GIS data will be useful to Caltrans for future climate adaptation planning activities.

4. TEMPERATURE

Temperature rise is a direct outcome of increased concentrations of GHGs in the atmosphere. Temperatures in the west are projected to continue rising and heat waves may become more frequent.[22] The potential effects of extreme temperatures on District 8 assets will vary by asset type and will depend on the specifications followed in the original design of the facility. For example, the following have been identified in other studies in the United States as potential impacts of increasing temperatures.

4.1. Design

- Pavement design includes an assessment of temperature in determining material.
- Ground conditions and more/less water saturation can alter the design factors for foundations and retaining walls.
- Temperature may affect expansion/contraction allowances for bridge joints.

4.2. Operations and Maintenance

- Extended periods of high temperatures will affect safety conditions for employees who work long hours outdoors, such as those working on maintenance activities.
- Right-of-way landscaping and vegetation must survive higher temperatures.
- Extreme temperatures could cause pavement discontinuities and deformation, which could lead to more frequent maintenance.

Resources available for this study did not allow for a detailed assessment of all the impacts temperature might have on Caltrans activities. Instead, it was decided to take a close look at one of the ways in which temperature will affect Caltrans: the selection of a pavement binder grade. Binder is essentially the “glue” that ties together the aggregate materials in asphalt. Selecting the appropriate and recommended pavement binder is reliant, in part, on the following:

- **Low temperature** – The mean of the absolute minimum air temperatures expected over a pavement’s design life.
- **High temperature** – The mean of the average maximum temperatures over seven consecutive days.

These climate metrics are critical to determining the extreme temperatures a roadway may experience over time. This is important to understand, because a binder must be selected that can maintain pavement integrity under both extreme cold conditions (which leads to contraction) and high heat (which leads to expansion).

The work completed for this effort included assessing the expected low and high temperatures for pavement binder specification in three future 30-year periods centered on the years 2025, 2055, and 2085. Understanding the metrics for these periods will enable Caltrans to gain insight on how pavement

[22] "Extreme Weather," U.S. National Climate Assessment, accessed April 29, 2019, http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather

design may need to shift over time. Per the Caltrans Highway Design Manual (HDM), the pavement design life for new construction and reconstruction projects shall be no less than 40 years. For roadside facilities, such as parking lots and rest areas, 20-year pavement design life may be used. The design life of asphalt pavements is close to the 30-year analysis periods used in this report. Because asphalt overlays of different specifications are often used to prolong roadway life, they can be used as short-term actions until it is clear how climate conditions are changing.

The project study team used the LOCA climate data developed by Scripps for this analysis of temperature,[23] which has a spatial resolution of 1/16 of a degree or approximately three and a half to four miles.[24] This data set was queried to determine the annual lowest temperature and the average seven-day consecutive high temperature. Temperature values were identified for each 30-year period. The values were derived separately for each of the 10 California appropriate GCMs, for both RCP scenarios, and for the three time periods noted.

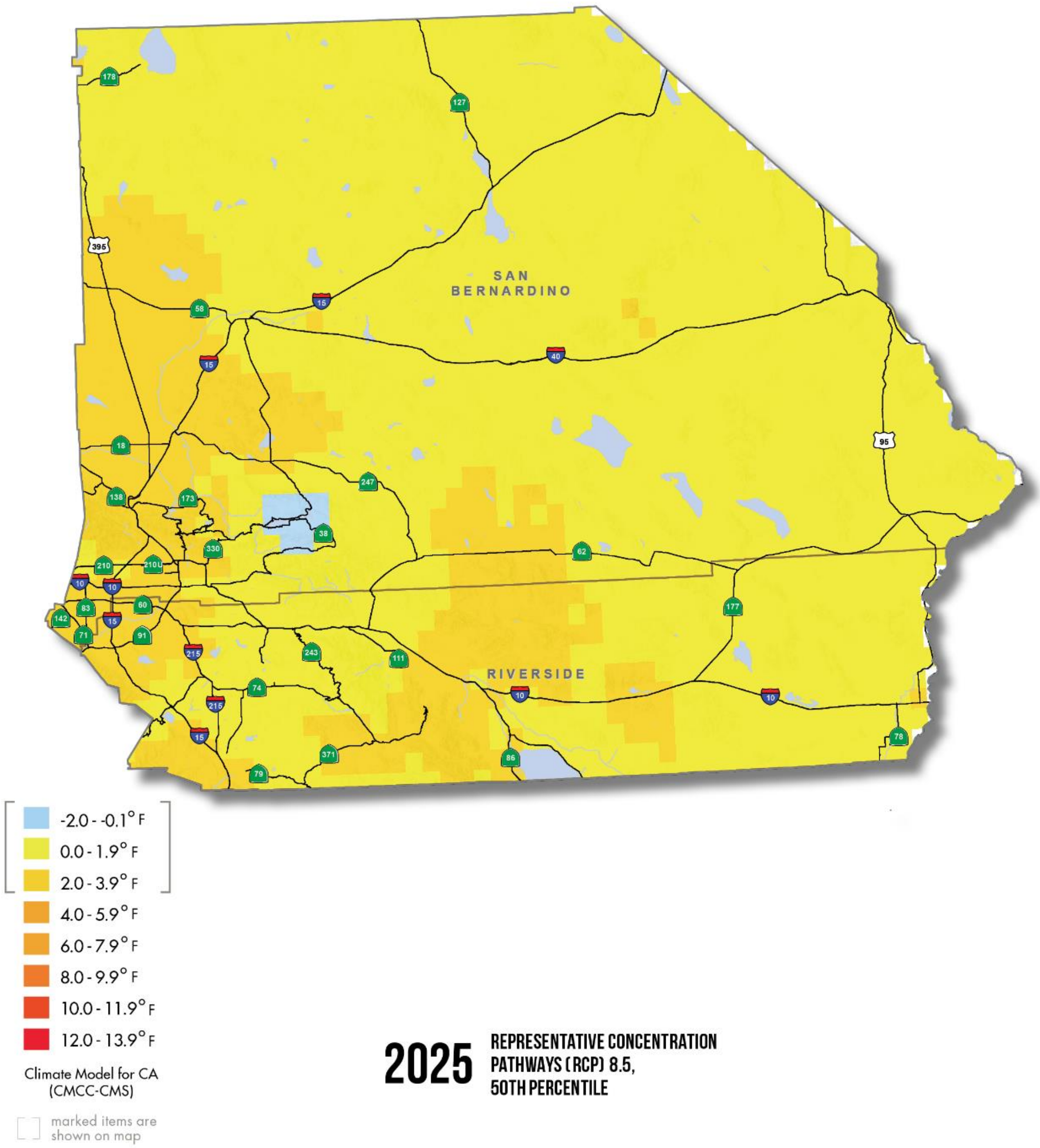
The maps shown are for the model that represents the median change across the state, among all California-approved climate models for RCP 8.5 (data for RCP 4.5 was analyzed, but for brevity is not shown here). The maps highlight the temperature change expected for both the maximum and minimum metrics. Both temperature metrics increase over time with the maximum temperature changes generally being greater than the minimum changes. Some areas may experience change in the maximum temperature metric upwards of 13.9 °F by the end of the century. Finally, for both metrics, temperature changes are generally greater further inland, due to the moderating influence of the Pacific Ocean. It is interesting to note that even with substantial elevation changes in the district, the higher elevation areas are impacted comparably.

The projected change shown on the maps provided in the following pages and can be added to Caltrans' current source of historical temperature data to determine final pavement design value for the future. This summarized data can be used by Caltrans to identify how pavement design practices may need to shift over time given the expected changes in temperature in the future and help inform decisions on how to provide the best pavement quality for California State Highway System users.

[23] A more detailed description of the LOCA data set and downscaling techniques can be found at the start of this report.
[24] "LOCA Downscaled Climate Projections," Cal-Adapt, last accessed May 1, 2019, http://cal-adapt.org/data/loca/

FIGURE 8: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2025

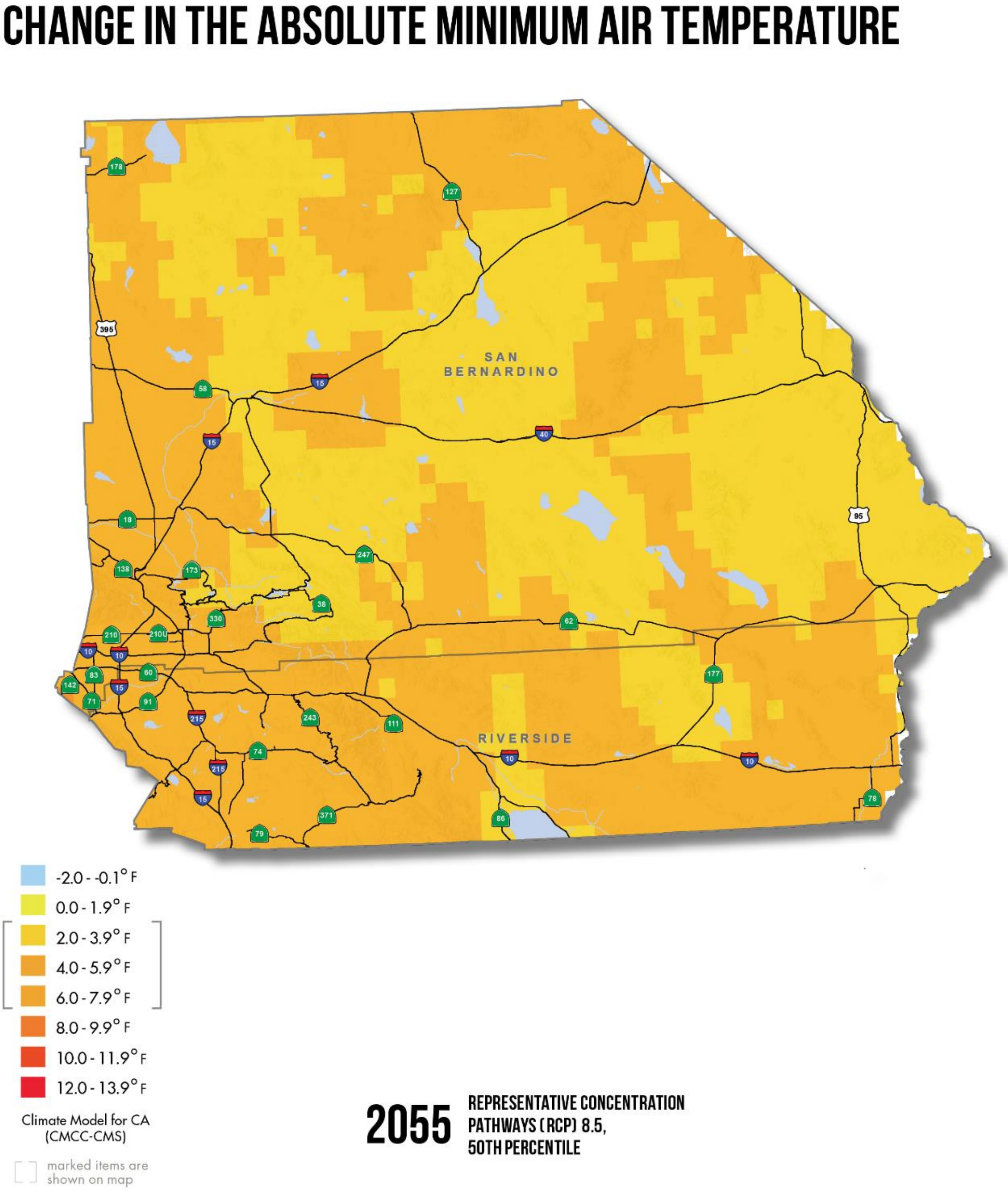
CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE



Future Change in the Absolute Minimum Air Temperature within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

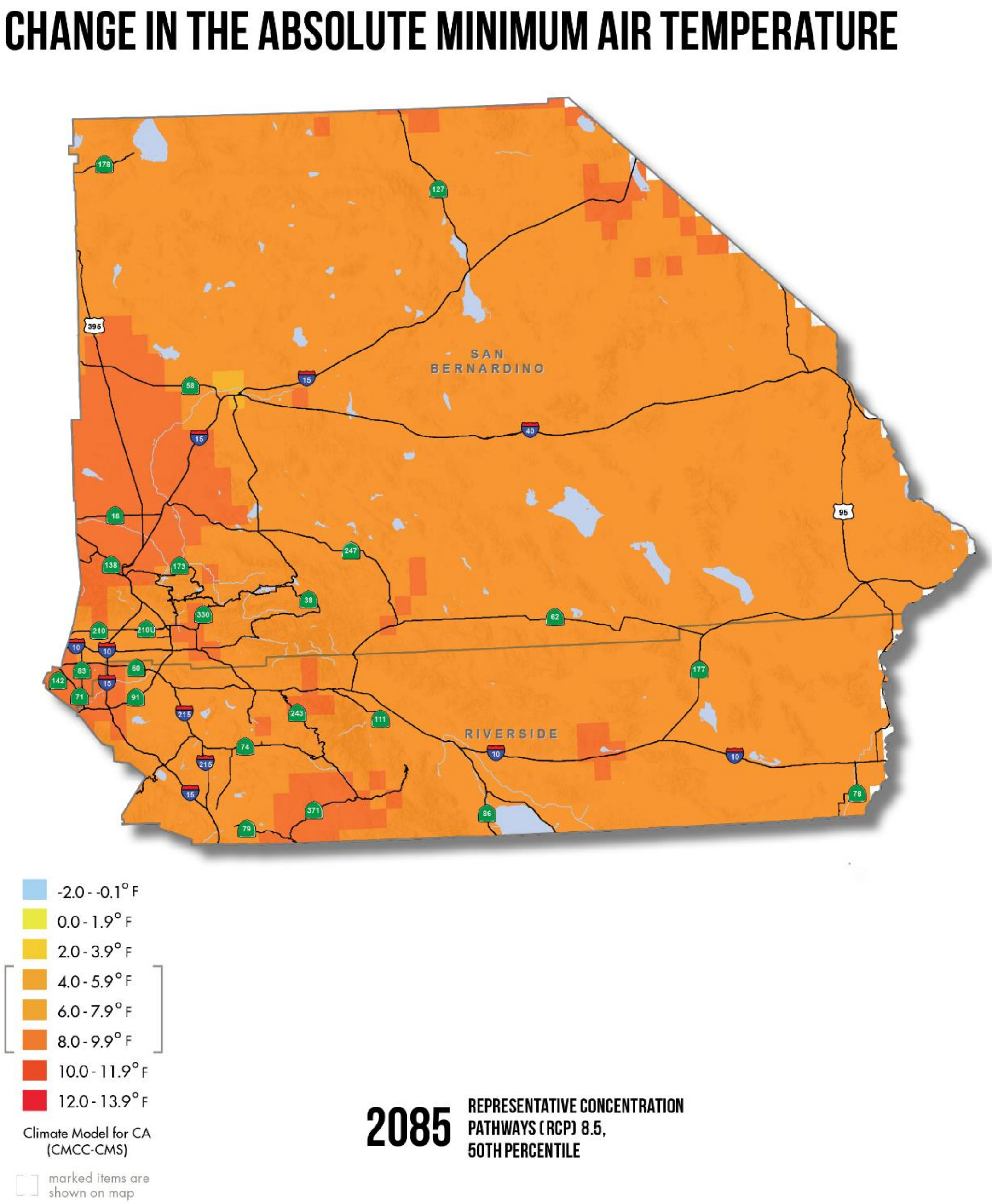
FIGURE 9: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2055



Future Change in the Absolute Minimum Air Temperature within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

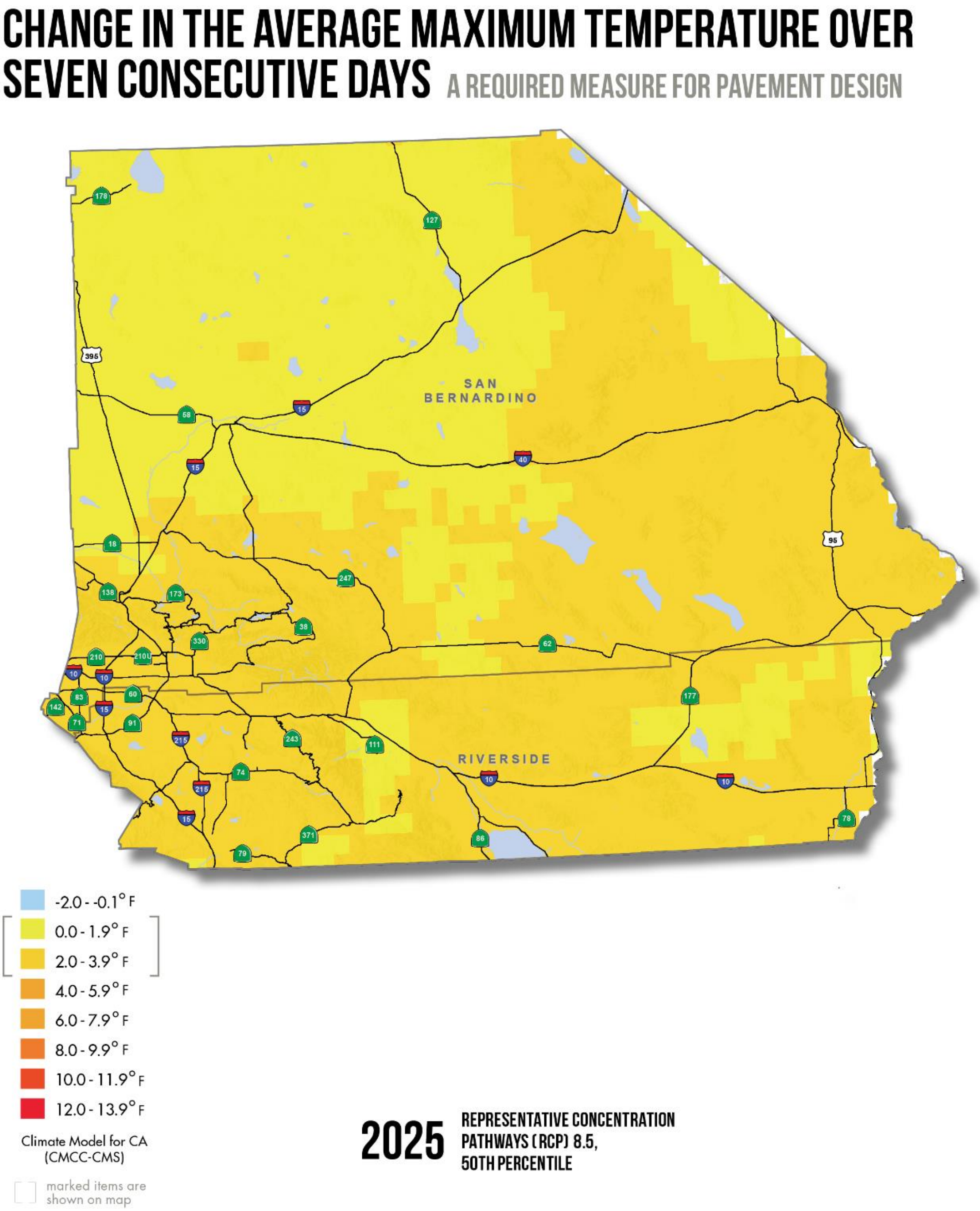
FIGURE 10: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2085



Future Change in the Absolute Minimum Air Temperature within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

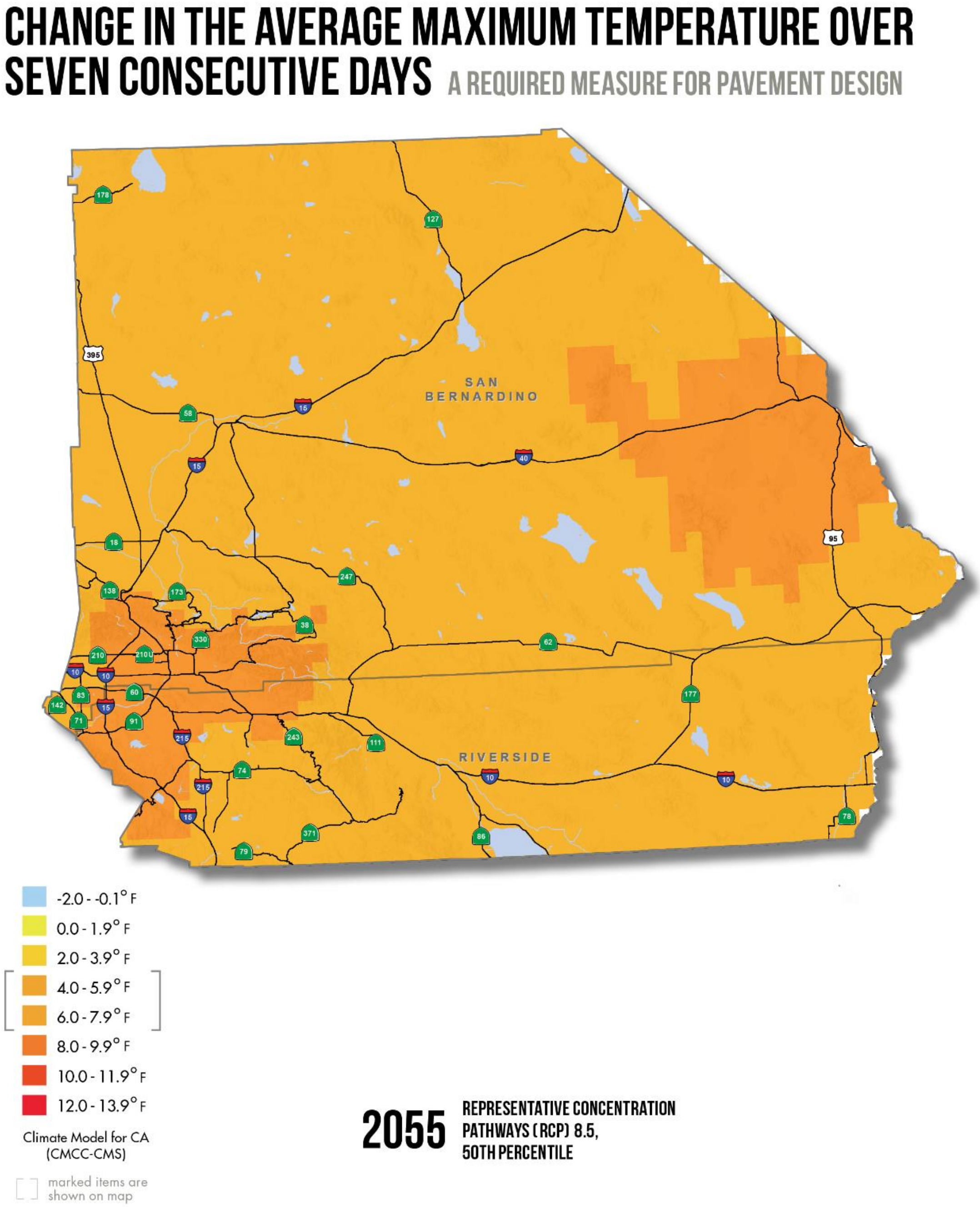
FIGURE 11: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2025



Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 12: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2055



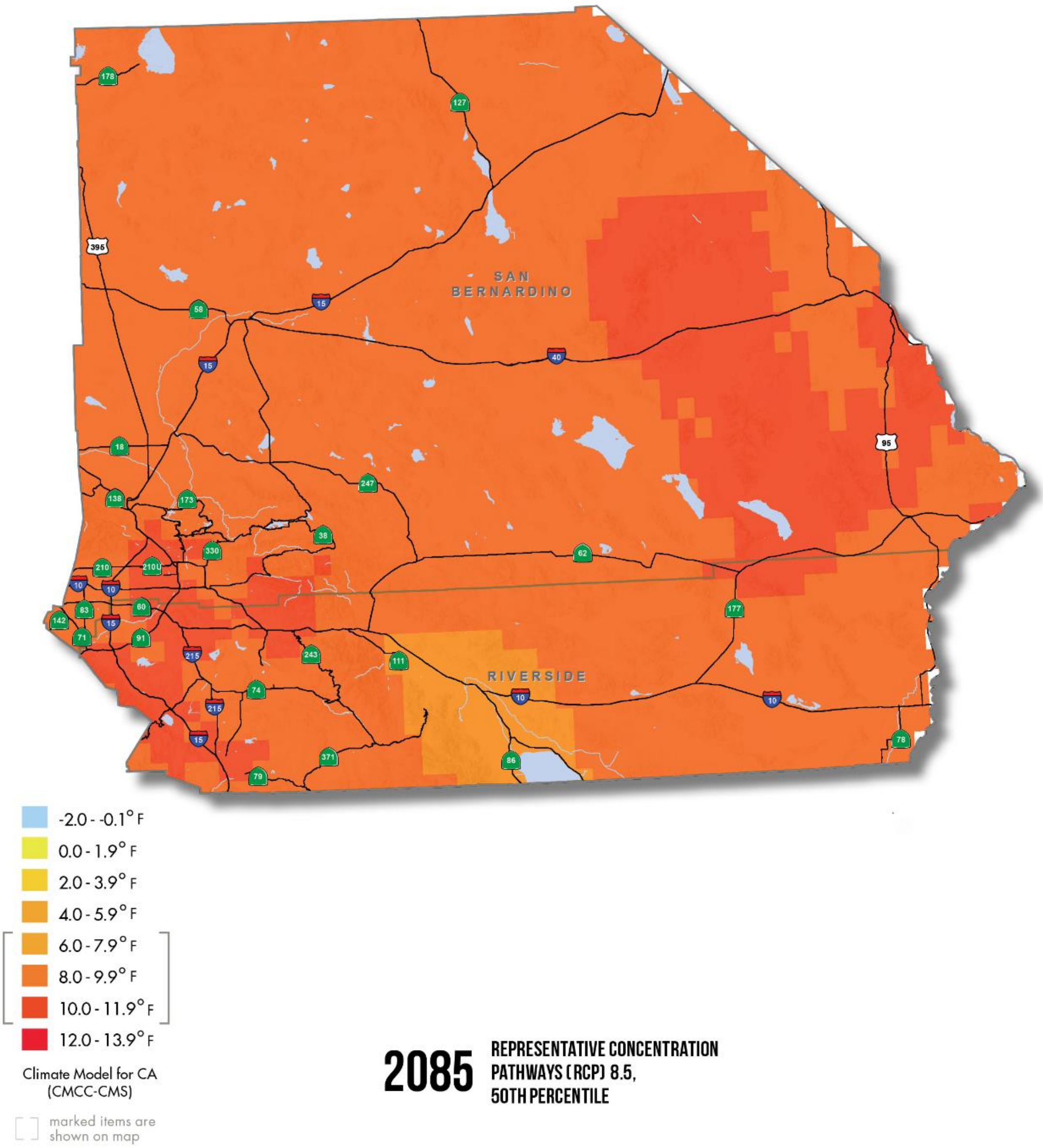
Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 13: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2085

CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS

A REQUIRED MEASURE FOR PAVEMENT DESIGN



Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

5. PRECIPITATION

The Southwest region of the United States has been identified as expecting less precipitation overall[25], but with the potential for heavier individual events, with more precipitation falling as rainfall. These conditions were experienced in District 8 during the 2016–2017 winter, where heavy precipitation caused millions in damages to Caltrans assets across the state. This section of this report focuses on how these heavy precipitation events may change and become more frequent over time. Current transportation design utilizes return period storm events as a variable to include in asset design criteria (e.g. for bridges, culverts). A 100-year design standard is often applied in the design of transportation facilities and is cited as a design consideration in Section 821.3, Selection of Design Flood, in the Caltrans Highway Design Manual.[26] Therefore, this metric was analyzed to determine how 100-year storm rainfall is expected to change.

Precipitation data is traditionally used at the project level by applying statistical analyses of historical rainfall, most often through the NOAA Atlas 14.[27] Rainfall values from the program are estimated across various time periods—from 5 minutes to 60 days. This data also shows how often rainfall of certain depths may occur in any given year, from an event that would likely occur annually, to one that would be expected to happen only once every 1,000 years. This information has been assembled based on rainfall data collected at rain gauges across the country.

Analysis of future precipitation is in many ways one of the most challenging tasks in assessing long-term climate risk. Modeled future precipitation values can vary widely. Thus, analysis of trends is considered across multiple models to identify predicted values and help drive effective decisions by Caltrans. Assessing future precipitation was done by analyzing the broad range of potential effects predicted by a set, or ensemble, of models.

Transportation assets in California are affected by precipitation in a variety of ways—from inundation/flooding, to landslides, washouts, or structural damage from heavy rain events. The project study team was interested in determining how a 100-year event may change over time for the purposes of analyzing vulnerabilities to the Caltrans SHS from inundation. Scripps currently maintains daily rainfall data for a set of climate models and two future emissions estimates for every day to the year 2100. The project study team worked with researchers from Scripps to estimate extreme precipitation changes over time. Specifically, the team requested precipitation data across the set of 10 international GCMs that were identified as having the best applicability for California.

This data was only available for the RCP 4.5 and 8.5 emissions scenarios and was analyzed for three time periods to determine how precipitation may change through the end of century. The years shown in the following figures represent the mid-points of the same 30-year statistical analysis periods as used for the temperature metrics.

[25] Melillo, Jerry, Terese (T.C.) Richmond, and Gary W. Yohe, “Climate Change Impacts in the United States: The Third National Climate Assessment,” U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2. (2014)
[26] Caltrans, “Highway Design Manual,” December 14, 2018, http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm
[27] National Oceanic and Atmospheric Administration, “Precipitation-Frequency Atlas of the United States,” 2018, https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume11.pdf

The project study team analyzed the models to understand two important points:

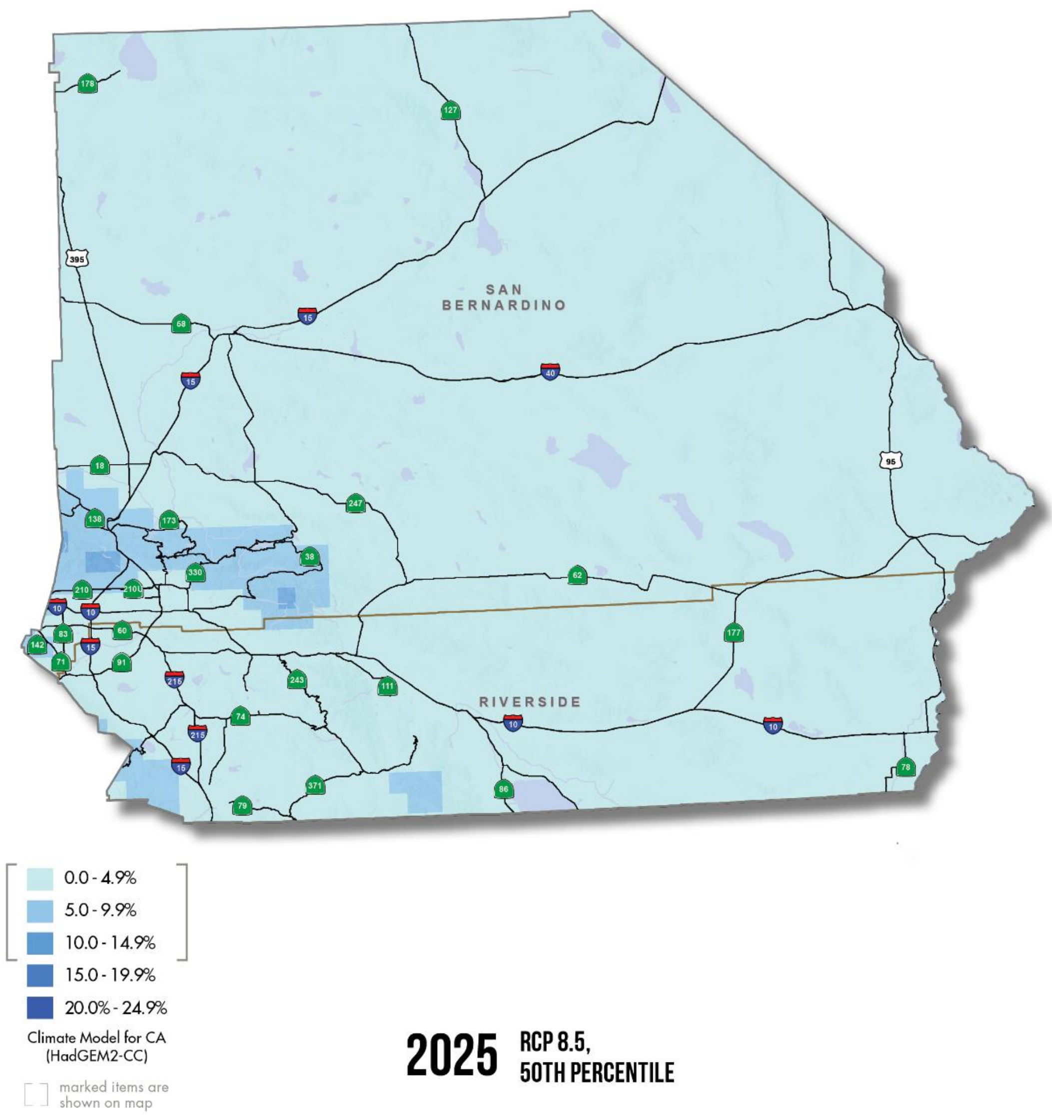
- Were there indications of change in return period storms across the models that should be considered in decision making when considering estimates for future precipitation?
- What was the magnitude of change for a 100-year return-period storm that should be considered as a part of facility design looking forward?

The results of this assessment are shown in the District 8 maps below. The three maps depict the percentage change in the 100-year storm rainfall event predicted for the three analysis periods, and for the RCP 8.5 emissions scenario (the RCP 4.5 results are not shown). The median model for the precipitation projections was used in this mapping given that it represents the mid-range forecasts out of a large range of projections. Choosing a model that provides low or high projections would not be appropriate in this case, as it could provide a distorted view of the future, given the high uncertainty and range in precipitation projections. Note that the change in 100-year storm depth is positive throughout District 8, indicating heavier rainfall during storm events

At first glance, the precipitation increases may appear to conflict with the wildfire analysis, which shows that wildfire events are expected to increase due to drier conditions. However, precipitation conditions in California are expected to change so that there are more frequent drought periods, but heavier, intermittent rainfall. These heavy storm events may have implications for the SHS and understanding those implications may help Caltrans engineers and designers implement an adaptive design solution. That said, a hydrological analysis of flood flows is necessary to determine how this data will affect specific bridges and culverts.

FIGURE 14: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2025

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

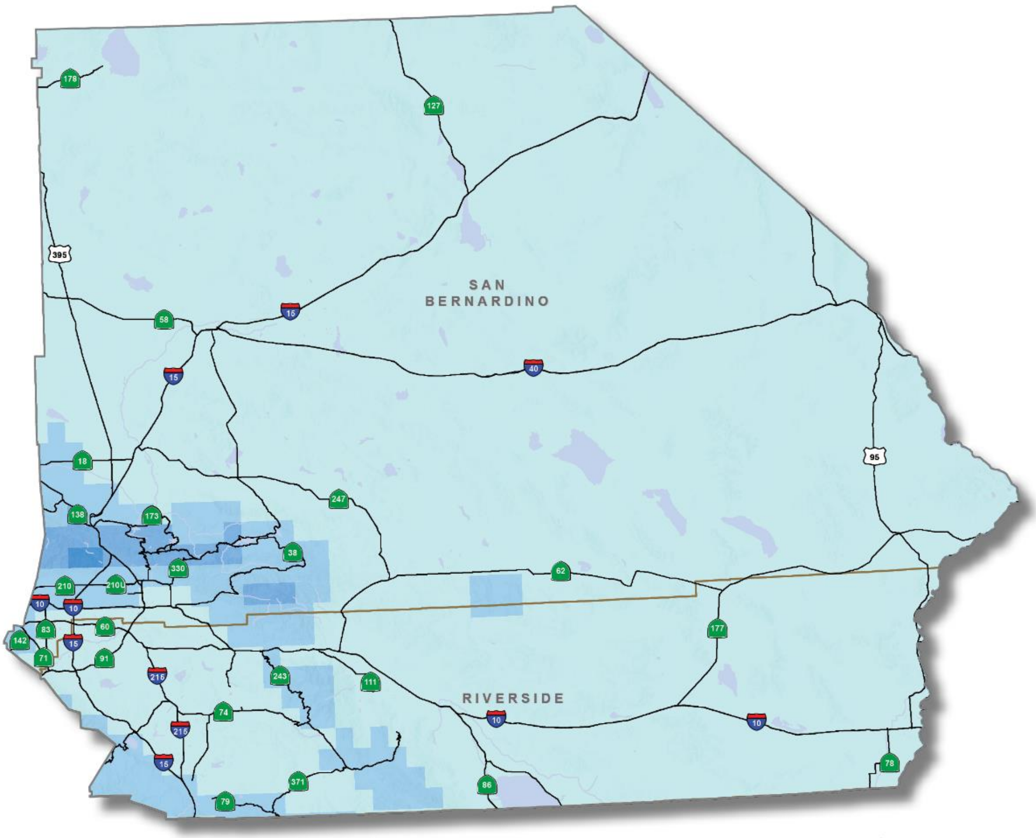


Future Percent Change in 100-year Storm Precipitation Depth within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 15: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2055

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH



0.0 - 4.9%
5.0 - 9.9%
10.0 - 14.9%
15.0 - 19.9%
20.0% - 24.9%

Climate Model for CA (HadGEM2-CC)

marked items are shown on map

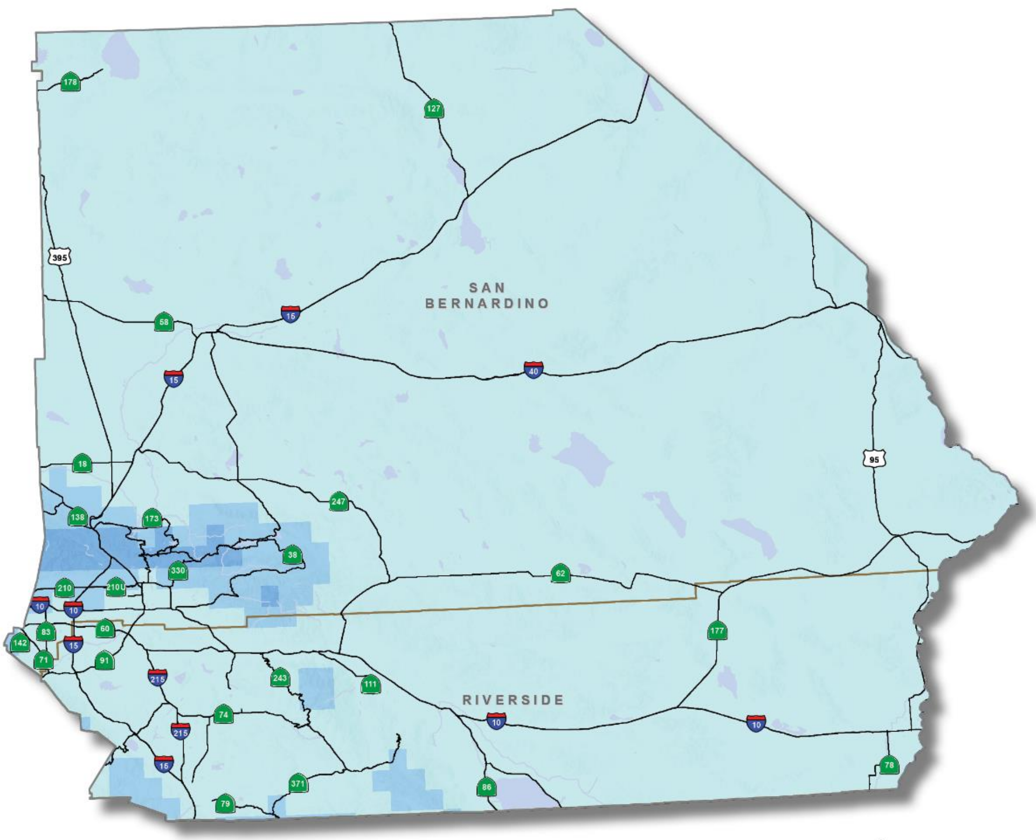
2055 RCP 8.5, 50TH PERCENTILE

Future Percent Change in 100-year Storm Precipitation Depth within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 16: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2085

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH



- 0.0 - 4.9%
- 5.0 - 9.9%
- 10.0 - 14.9%
- 15.0 - 19.9%
- 20.0% - 24.9%

Climate Model for CA (HadGEM2-CC)

marked items are shown on map

2085 RCP 8.5, 50TH PERCENTILE

Future Percent Change in 100-year Storm Precipitation Depth within District 8, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 8. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

6. WILDFIRE

Increasing temperatures, changing precipitation patterns, and resulting changes to land cover, are expected to affect wildfire frequency and intensity. Human infrastructure, including the presence of electrical utility infrastructure, or other sources of fire potential (mechanical, open fire, accidental or intentional) may also influence the occurrence of wildfires. Wildfire is a direct concern for driver safety, system operations, and Caltrans infrastructure, among other issues.

Wildfires can indirectly contribute to:

- Landslide and flooding exposure, by burning off soil-stabilizing land cover and reducing the capacity of the soils to absorb rainfall.
- Wildfire smoke, which can affect visibility and the health of the public and Caltrans staff.

The last few months of 2017 were notable for the significant wildfires that occurred both in Northern and Southern California. These devastating fires caused property damage, loss of life, and damage to roadways. In 2018, the major wildfires in District 8 included the Holy Fire which burned 23, 136 acres and destroyed 18 structures near SR-74. The Cranston Fire burned 13,139 acres and injured two people. The costs to Caltrans of repairing such damage caused by wildfires could extend over months for individual events. The conditions that contribute to many wildfire impacts, notably a wet rainy season followed by very dry conditions and heavy winds, are likely to occur again in the future as climate conditions change and storm events become more dynamic.

The information gathered and assessed to develop wildfire vulnerability data for District 8 included research on the effect of climate change on wildfire recurrence. This is of interest to several agencies, including the U.S. Forest Service (USFS), the Environmental Protection Agency (EPA), the Bureau of Land Management (BLM), the California Department of Forestry and Fire Protection (CalFire), some of which have developed their own models to understand the trends of future wildfires throughout the US and in California.

6.1. Ongoing Wildfire Modeling Efforts

Determining the potential impacts of wildfires on the SHS included coordination with other agencies that have developed wildfire models for various applications. Models used for this analysis included the following:

- **MC2 - EPA** Climate Impacts Risk Assessment (CIRA), developed by John Kim, USFS
- **MC2 - Applied Climate Science Lab (ACSL)** at the University of Idaho, developed by Dominique Bachelet, University of Idaho
- **University of California Merced model,** developed by Leroy Westerling, University of California Merced

The MC2 models are second generation models, developed from the original MC1 model made by the USFS. The MC2 model is a Dynamic Global Vegetation Model, developed in collaboration with Oregon

State University. This model considers projections of future temperature, precipitation and changes these factors will have on vegetation types/habitat area. The MC2 model outputs used for this assessment are from the current IPCC Coupled Model Intercomparison Project 5 (CMIP5) dataset. This model was applied in two different studies of potential wildfire impacts at a broader scale by researchers at USFS of the University of Idaho. The application of the vegetation model and the expectation of changing vegetation range/type is a primary factor of interest in the application of this model.

The second wildfire model used was developed by Leroy Westerling at the University of California, Merced. This statistical model was developed to analyze the conditions that led to past large fires (defined as over 1,000 acres) in California, and uses these patterns to predict future wildfires. Inputs to the model included climate, vegetation, population density, and fire history. This model then incorporated future climate data and projected land use changes to project wildfire recurrence in California to the year 2100.

Each of these wildfire models used inputs from downscaled climate models to determine future temperature and precipitation conditions that are important for projecting future wildfires. The efforts undertaken by the EPA/USFS and UC Merced used the LOCA climate data set developed by Scripps, while the University of Idaho effort used an alternative downscaling method, the Multivariate Adaptive Constructed Analogs (MACA).

For the purposes of this report, these three available climate models will be identified from this point forward as:

- MC2 - EPA
- MC2 - University of Idaho
- UC Merced/Westerling

6.2. Global Climate Models Applied

Each of the efforts used a series of GCM outputs to generate projections of future wildfire conditions. In this analysis, the project study team used the four recommended GCMs from Cal-Adapt for wildfire outputs (CAN ESM2, CNRM-CM5, HAD-GEM2-ES, MIROC5). In addition, all three of the modeling efforts used RCPs 4.5 and 8.5, representing realistic lower and higher ranges for future GHG emissions. Table 1 graphically represents the wildfire models and GCMs used in the assessment.

TABLE 1: WILDFIRE MODELS AND ASSOCIATED GCMS USED IN WILDFIRE ASSESSMENT

Wildfire Models								
MC2 - EPA			MC2 - ACSC			UC Merced		
CAN ESM2	HAD-GEM2-ES	MIROC5	CAN ESM2	HAD-GEM2-ES	MIROC5	CAN ESM2	HAD-GEM2-ES	MIROC5

6.3. Analysis Methods

The wildfire projections for all model data were developed for the three future 30-year time periods used in this study (median years of 2025, 2055, and 2085). These median years represent 30-year averages, where 2025 is the average between 2010 and 2039, and so on. These are represented as such on the wildfire maps that follow.

The wildfire models produce geospatial data in raster format, which is data that is expressed in individual "cells" on a map. The final wildfire projections for this effort provides a summary of the percentage of each of these cells that burns for each time period. The raster cell size applied is 1/16 of a degree square for the MC2 - EPA and UC Merced/Westerling models, which matches the grid cell size for the LOCA climate data applied in developing these models. The MC2 - University of Idaho effort generated data at 1/24 of a degree square, to match the grid cells generated by the MACA downscaling method.

The model data was collected for all wildfire/GCM combinations, for each year to the year 2100. Lines of latitude (the east to west lines on the globe) are essentially evenly spaced when measuring north to south; however, lines of longitude (the north-south lines on the globe, used to measure east-west distances) become more tightly spaced as they approach the poles, where they eventually converge. Because of this, the cells in the wildfire raster are rectangular instead of square and are of different sizes depending on where one is (they are shorter when measured east-west as you go farther north). The study team ultimately summarized the data into the 1/16th grid to enable comparisons and to summarize across multiple models. The resulting area contained within these cells ranged in area between roughly 8,000 and 10,000 acres for grid cells sizes that are 6 kilometers on each side.

An initial analysis of the results of the wildfire models for the same time periods for similar GCMs noted differences in the outputs of the models, in terms of the amount of burn projected for various cells. This difference could be caused by any number of factors, including the assumption of changing vegetation that is included in the MC2 models, but not in the UC Merced/Westerling model.

6.4. Categorization and Summary

The final method selected to determine future wildfire risks throughout the state takes advantage of the presence of three modeled datasets to generate a broader understanding of future wildfire exposure in California. The project team determined this would provide a more robust result than applying only one of the available wildfire models. A cumulative total of percentage cell burned was developed for each cell in the final dataset. This data is available for future application by Caltrans and their partners.

As a means of establishing a level of concern for wildfire impacts, a classification was developed based on the expected percentage of cell burned. The classification is as follows:

- Very Low 0-5%,
- Low 5-15%,
- Moderate 15-50%,
- High 50-100%,

- Very High 100%+.[28]

Thus, if a cell were to show a complete burn or higher (8,000 to 10,000 acres+) over a 30-year period, that cell was identified as a very high wildfire exposure cell. Developing this categorization method included removing the CNRM-CM5 data point from the MC2 - University of Idaho and UC Merced/Westerling datasets to have three consistent points of data for each cell in every model. This was done to provide a consistent number of data points for each wildfire model.

Next, the project study team looked at results across all models to see if any one wildfire model/GCM model combination indicated a potential exposure concern in each grid cell. The categorization for any one cell in the summary identifies the highest categorization for that cell across all nine data points analyzed. For example, if a wildfire model result identified the potential for significant burn in any one cell, the final dataset reflects this risk. This provides Caltrans with a more conservative method of considering future wildfire risk.

Finally, the project study team assigned a score for each cell where there is relative agreement on the categorization across all the model outputs. An analysis was completed to determine whether 5 of the 9 data points for each cell (a simple majority) were consistent in estimating the percentage of cell burned for each 30-year period. Figure 17 through Figure 19 on the following pages show the results of this analysis, using the classification scheme explained above and RCP 8.5.[29] Table 2 and Table 3 summarize the centerline miles of the District 8 State Highway System that are exposed to moderate to very high wildfire risk, by year, District 8 county, and RCP scenario.

TABLE 2: CENTERLINE MILES OF STATE HIGHWAY SYSTEM EXPOSED TO MODERATE TO VERY HIGH WILDFIRE CONCERN FOR THE RCP 8.5 SCENARIO

	Year		
District 8 Counties	**2025**	**2055**	**2085**
Riverside	205.1	227.3	240.7
San Bernardino	282.7	333.6	422.7

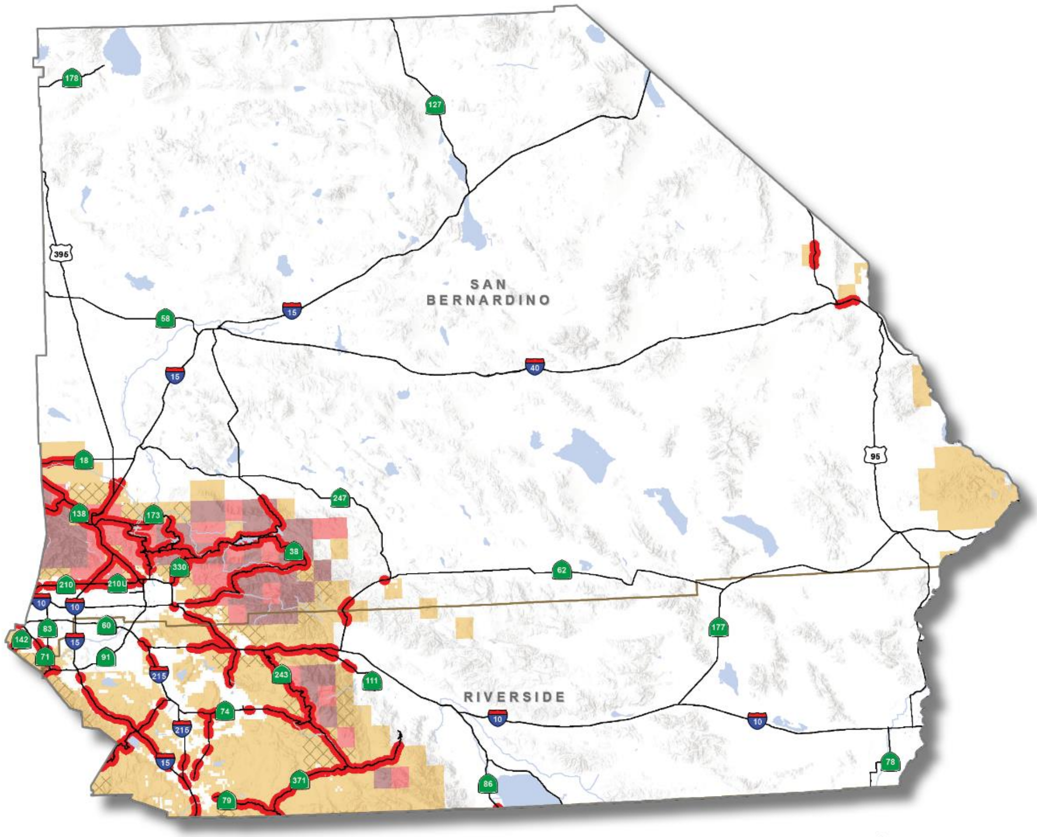
TABLE 3: CENTERLINE MILES OF STATE HIGHWAY SYSTEM EXPOSED TO MODERATE TO VERY HIGH WILDFIRE CONCERN FOR THE RCP 4.5 SCENARIO

	Year		
District 8 Counties	**2025**	**2055**	**2085**
Riverside	199.0	179.7	183.6
San Bernardino	262.4	264.9	270.3

[28] A cell can have greater than 100% burn if burned twice or more in the same time period.
[29] Areas on the maps shown in white do not necessarily have no associated wildfire risk - the classification is below moderate.

FIGURE 17: INCREASE IN WILDFIRE EXPOSURE 2025

LEVEL OF WILDFIRE CONCERN



Levels of Concern

- VERY HIGH
- HIGH
- MEDIUM
- HIGH MODEL AGREEMENT*
- EXPOSED ROADWAY

2025 RCP 8.5, MULTI-MODEL MAXIMUM

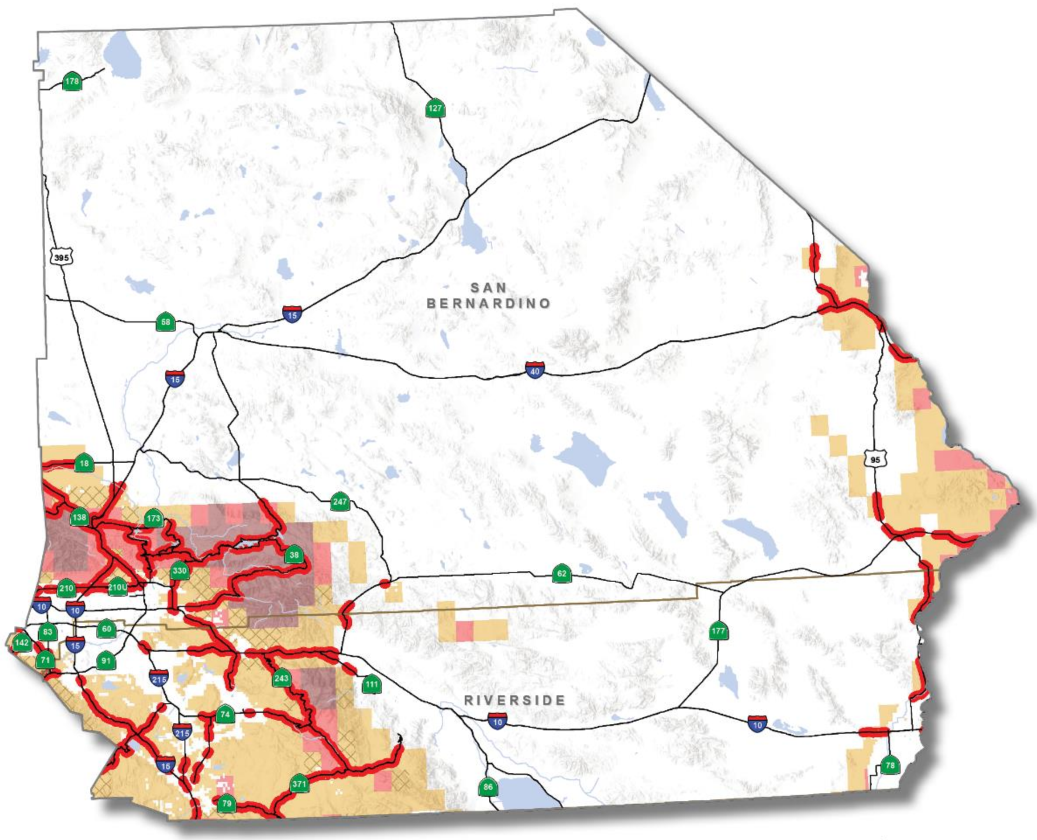
Future Level of Wildfire Concern for the Caltrans State Highway System within District 8, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

FIGURE 18: INCREASE IN WILDFIRE EXPOSURE 2055

LEVEL OF WILDFIRE CONCERN



Levels of Concern

- VERY HIGH
- HIGH
- MEDIUM
- HIGH MODEL AGREEMENT*
- EXPOSED ROADWAY

2055 **RCP 8.5, MULTI-MODEL MAXIMUM**

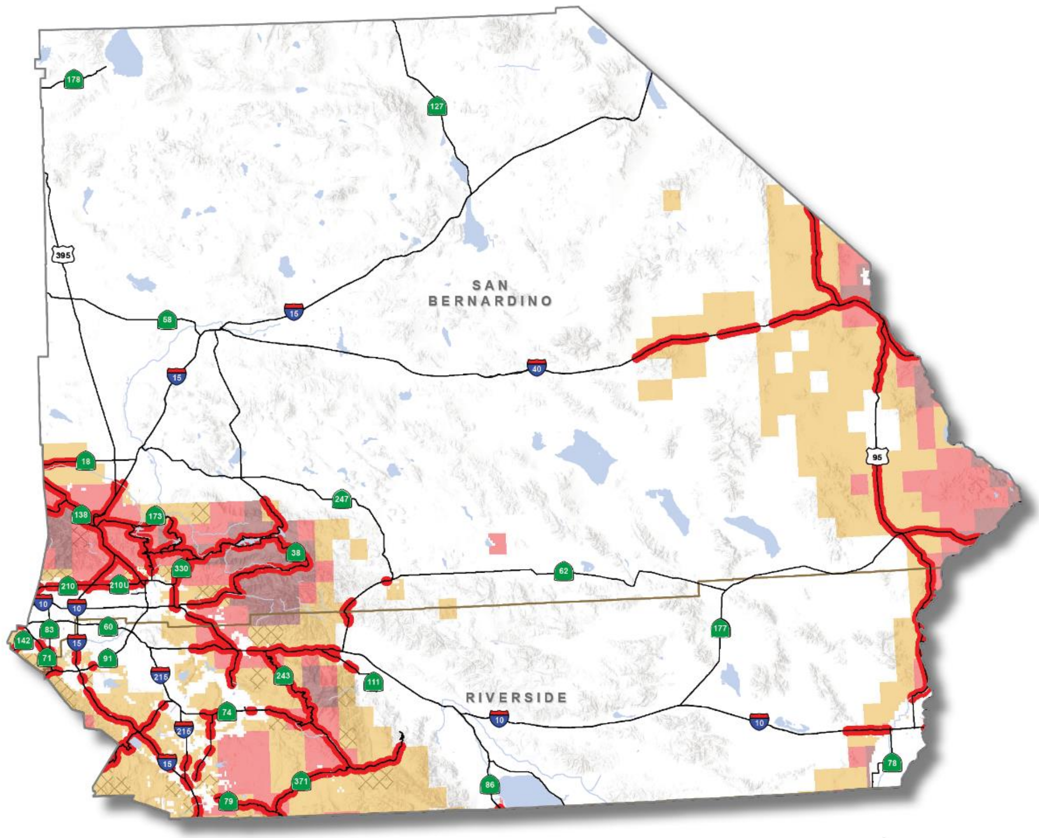
Future Level of Wildfire Concern for the Caltrans State Highway System within District 8, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

FIGURE 19: INCREASE IN WILDFIRE EXPOSURE 2085

LEVEL OF WILDFIRE CONCERN



Levels of Concern

- VERY HIGH
- HIGH
- MEDIUM
- HIGH MODEL AGREEMENT*
- EXPOSED ROADWAY

2085 **RCP 8.5, MULTI-MODEL MAXIMUM**

Future Level of Wildfire Concern for the Caltrans State Highway System within District 8, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

7. LOCAL EXAMPLE OF EXTREME WEATHER IMPACTS

As climate changes, California could be affected by more frequent, extreme weather events. In recent years, California has been through a severe drought (2011 – 2017), a series of extreme storm events that caused flash flooding and landslides across the state (2017 – 2018), the worst wildfire season on record (2017), and deadly mudslides in Southern California (2018). While it is impossible to directly link any one of these events to be caused solely by climate change, these emergencies demonstrate what could become more commonplace for California in the future. It is important to learn from these events, take actions to prevent them wherever possible, and increase the resiliency of transportation infrastructure for near- and long-term threats. This section provides an example of a weather-related event at the district level and the district response.

I-10 Tex-Wash Bridge Washout

On July 19, 2015, the eastbound Highway 10 Tex Wash Bridge collapsed after a flash flood brought water, mud, and debris through a previously dry riverbed (the Tex Wash). The US National Weather Service found the heavy storm event to be caused by Hurricane Dolores' remaining moisture and circulation, which created perfect conditions for flooding in southeast California. Seventeen centimeters of rain fell in six hours and the flood was determined to be a 1,000-year storm event.[30]

A failure analysis of the collapse found that it was caused by a combination of weather factors and bridge design flaws (see Figure 20 and Figure 21 for photos of the collapse). The main factors that contributed to the bridge failure were:

- The shape of the wash, which caused a bottleneck in the path of the food
- Flood waters which made an "S" curve due to the shape of the wash and directed flow at, and washed soil out from under, the east abutment
- The erosion of the fill soil on which the east abutment was supported
- The abutment wing walls perpendicular alignment to the flood waters which exposed more surface area to the water's force
- The combination of the above effects which knocked over the abutment and caused the deck to collapse.[31]

Approximately 4,480 trucks cross the bridge daily[32] so its collapse resulted in severe traffic delays. Caltrans responded quickly to the initial event and reopened the bridge to traffic just three days later. Next actions included the complete demolition of the collapsed bridge, replacement of rock slope protection in the wash, and the design of a new bridge that used piles instead of spread footing to make the structure more resilient to similar events. The new

[30] Maryam Tabbakhha, Abolhassan Astaneh-Asl, Daniel Christian Setioso, "Failure Analysis of Flood Collapse of the Tex Wash Bridge," University of California at Berkeley, *Proceedings of the World Congress on Civil, Structural, and Environmental Engineering,* Paper No. ICSENM 118 (2016): DOI: 10.11159/icsenm16.118, https://avestia.com/CSEE2016_Proceedings/files/paper/ICSENM/118.pdf
[31] Ibid.
[32] Ibid.

bridge was built through accelerated bridge construction (ABC) and was reopened just 67 days after the collapse.[33]

FIGURE 20: TEX WASH BRIDGE ABUTMENT AND DECK COLLAPSE

[33] Mike Keat, "Precast Concrete Speeds California Bridge Replacement," American City & County, July 26, 2016, https://www.americancityandcounty.com/2016/07/26/precast-concrete-speeds-california-bridge-replacement/

8. INCORPORATING CLIMATE CHANGE INTO DECISION-MAKING

8.1. Risk-Based Design

A risk-based decision approach considers the broader implications of damage and economic loss in determining the approach to design. Climate change is a risk factor that is often omitted from design, but is important for an asset to function over its design life Incorporating climate change into asset-level decision-making has been a subject of research over the past decade, much of it led or funded by the Federal Highway Administration (FHWA). The FHWA undertook a few projects to assess climate change and facility design – including the Gulf Coast II project (Mobile, AL) and the Transportation Engineering Approaches to Climate Resiliency Study. Both assessed facilities of varying types, which were exposed to different climate stressors. They then identified design responses that could make the facilities more resilient to change.

One outcome of the FHWA studies was a step-by-step method for completing facility (or asset) design, such that climate change was considered and inherent uncertainties in the timing and scale of climate change were included. This method, termed the Adaptation Decision-Making Assessment Process (ADAP),[34] provides facility designers with a recommended approach to designing a facility when considering possible climate change effects. The key steps in ADAP are shown in Figure 22: FHWA's Adaptation Decision-Making Process.

The first five steps of the ADAP process cover the characteristics of the project and the context. The District 8 Vulnerability Assessment has worked through these first steps at a high level. The data and results of this analysis, along with a follow-up adaptation study for the district, will be useful to District staff in future asset- and facility-level analyses. These five steps should be addressed for every exposed facility during asset level analyses.

Step five focuses on conducting a more detailed assessment of the performance of the facility. When analyzing one facility, it is important to assess the highest impact scenario. This does not necessarily correspond to the highest temperature range, or largest storm event. In this case, the analysis should determine which scenarios will have the greatest effect on a facility. For example, a 20-year storm may cause greater impacts than a 100-year storm, depending on wind and wave directions. If the design criteria of the facility are met even under the greatest impact scenario, the analysis is complete. Otherwise, the process moves onto developing adaptation options.

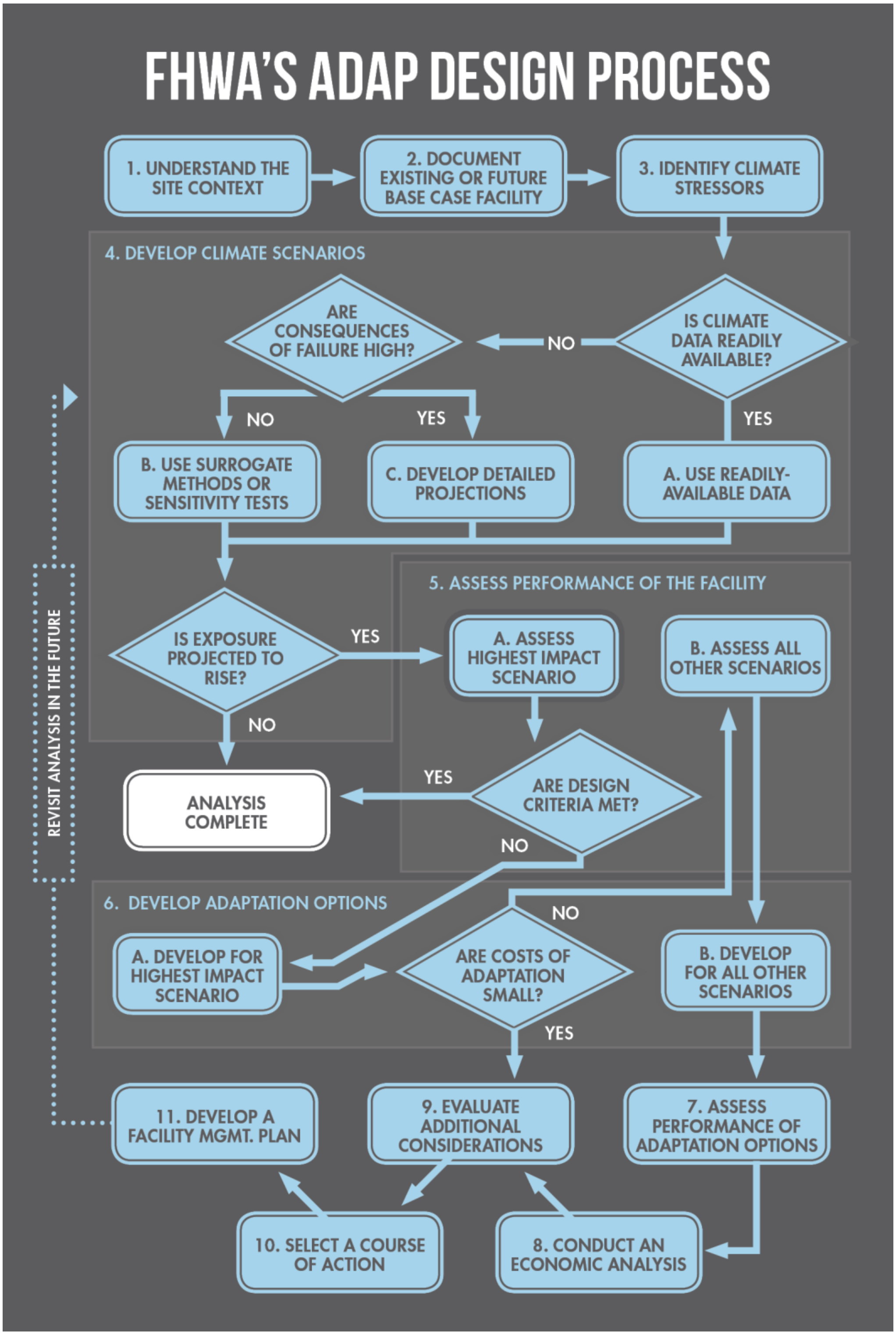
Options should be developed that will adapt the facility to the highest impact scenario. If these options are affordable, they can move to the final steps of the process. If they are not, other scenarios can be considered to identify more affordable options. These alternative design options will need to move through additional steps to critique their performance and economic value. Then, they also move to the final steps of the process. These last three steps are critical to implementing adaptive designs. Step nine involves considering other factors that may influence adaptation design and implementation. For example, California Executive Order B-30-15 requires consideration of:

[34] "Adaptation Decision-Making Assessment Process," FHWA, last modified January 12, 2018. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm

- full life cycle cost accounting
- maladaptation,
- vulnerable populations,
- natural infrastructure,
- adaptation options that also mitigate greenhouse gases,
- and the use of flexible approaches where necessary.

At this step in the ADAP process, it is important to understand the greater context of the designs developed and whether they meet state, Caltrans, and/or other requirements. This also allows for the opportunity to consider potential impacts of the project outside of design and economics, including how it may affect the surrounding community and environment. After evaluating these additional considerations, a course of action can be selected and a facility management plan can be implemented.

FIGURE 22: FHWA'S ADAPTATION DECISION-MAKING PROCESS



For additional information about ADAP please see the FHWA website at: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm

8.2. Highway 74 Landslide and Mitigation Measures

The following provides an example of a District 8 response to an extreme weather related impact, specifically a landslide following a wildfire. While not directly attributable to climate change, this example provides some insight into how District 8 is affected by such events, and how the district responds to address the event and mitigate future risk.

In August 2009, the Cottonwood Fire burned for four days along both sides of Highway 74 in Riverside County between Hemet and Idyllwild. The road was closed for a few days in 2009, but landslides and mudslides in the same location forced its closure again in 2014.[35] Caltrans responded with landslide mitigation measures to stabilize the slope and control water flow, but in 2017 another storm event triggered the Cranston Landslide which compromised these stabilization efforts. Again, Caltrans responded by repairing culverts, identifying separations in the drainage systems, repairing surficial erosion such as gullies, and installing straw wattles and sandbags to control surface runoff.[36] While this example does not incorporate risk-based design, it demonstrates the effort required to maintain and stabilize high risk areas.

8.3. Project Prioritization

The project prioritization approach outlined below is based on a review of the methods in other transportation agencies, and lessons learned from other adaptation efforts. These methods—mostly developed and used by departments of transportation in other states—address long-term climate risks and are intended to inform project priorities across the range of diverse project needs. The method outlined below recognizes the following issues when considering climate change adaptation for transportation projects:

- The implications of damage or failure to a transportation facility due to climate change-related stresses.
- The likelihood or probability of occurrence of an event.
- The timeframe at which the events may occur, and the shifting of future risks associated with climate change.

The recommended prioritization method is applied to those facilities with high exposure to climate change risk; thus, it is not applied to the entire transportation network. The method assumes that projects have been defined in sufficient detail to allow some estimate of implementation costs.

Some guiding principles for the development of the prioritization method included the following:

- It should be straightforward in application, easily discernable, describable and it should be relatively straightforward to implement with common software applications (Excel, etc.).
- It should be based on best practices in the climate adaptation field.

[35] "Crews Gain Ground on Cottonwood Fire," NBC Los Angeles, August 30, 2009, https://www.nbclosangeles.com/news/local/Crews-Gain-Ground-on-Cottonwood-Fire-56226382.html
[36] "Highway 74 Reopens After Landslide," KESQ, last modified August 28, 2016, https://www.kesq.com/home/hwy-74-reopens-after-landslide/62498169

- It should avoid weighting schemes and multi-criteria scoring, since those processes tend to be difficult to explain and are open to interpretation among professionals with varying perspectives.
- It should be focused on how departments of transportation do business, reflect priorities for program delivery to stakeholders and recognize the relative importance of various assets.
- It should have the ability to differentiate between projects that may have different implications of risk—like near-term minor impacts and long-term major impacts—to set project priorities.
- It should facilitate decisions among different project types, for example, projects for repairs or for continuous minor damage as compared to one-time major damage events.
- It should enable the comparison among all types of projects, regardless of the stressor causing impacts.

The prioritization method requires the following information:

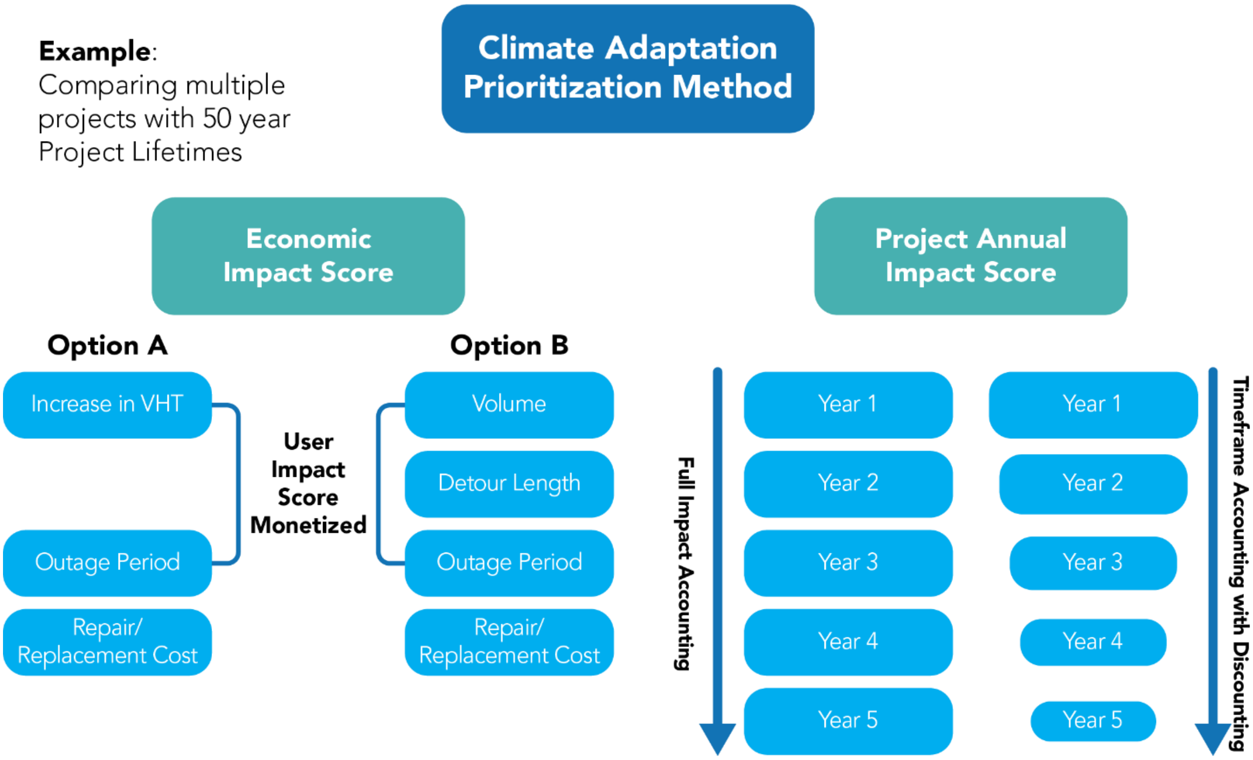
- Facility loss/damage estimates (supplied by Caltrans engineering staff) should capture both lower level recurring impacts and larger loss or damage. These should include a few key pieces of information, including:
  - What are the levels for stressors (SLR, surge, wildfire, etc.) that would cause damage and or loss?
  - What are the implications of this damage in terms of cost to repair and estimated time to repair?
- System impacts (supplied by Caltrans planning staff) – the impacts of the loss of the facility on the broader system. This could be in terms of increase in Vehicle Hours Traveled (VHT) if using a traffic model, or an estimated value using volume and detour length as surrogates.
- Probability of occurrence (supplied by Caltrans climate change staff through coordination with state climate experts) – the probability of events occurring as estimated from the climate data for chosen climate scenarios. Estimated for each year out to the end of the facility lifetime.

A project annual impact score is used to reflect two conditions, summarized by year:

- The expected cumulative loss estimated for the project over the project lifetime (full impact accounting).
- A method of discounting losses over years– to enable prioritization based on nearer term or longer-term expected impacts (timeframe accounting).

These two pieces of information are important to better understand the full cost of impacts over time. Figure 23 shows the general approach for the prioritization method.

FIGURE 23: APPROACH FOR PRIORITIZATION METHOD



The two side-by-side charts represent various approaches to calculating values to be used for prioritization. The left side (Economic Impact Score) shows two methods for determining costs to the system user. The right-side show how costs could be counted in two ways, one which utilizes a full impact accounting that basically sums all costs to the end of the asset useful life while the other uses annual discounting to reflect "true costs" or current year dollar equivalent values to calculate the final impact score for the asset. These are presented as shown in part to provide an option for determining these values and in part to outline the various methods that are being used on similar projects nationally. The final selected method would require input and leadership from Caltrans to define the parameters for the approach to inform decisions.

The prioritization method would need estimates of at a minimum repair/replacement cost (dollars) and, if broadened, a system users impact (in dollar equivalents). System user costs would be summarized for this effort as transportation service impacts, and would be calculated in one of two ways:

- Estimate the impacts to a transportation system by identifying an expected detour routing that would be expected with loss of access or a loss/damage climate event. This value would be combined with average daily traffic and outage period values to result in an estimate of VHT increase associated with the loss of use of a facility.
- Utilize a traffic model to estimate the impacts on the broader State Highway System from damage/loss of a facility or facilities anticipated to occur as a result of a climate event. The impact on the system would be summarized based on the net increase in VHT calculated in the model.

The advantage of the system method is that it determines impacts of multiple loss/failure assessments consecutively and is not confined to only the assessment of each individual project as an individual project concern. It also allows for comparisons to the broader system and scores facilities with heavier use and importance to an integrated system as higher in terms of impact and prioritization.

Probabilities of an event occurring over each year would be used to summarize costs per year as well as a summarized cumulative total cost for the project over the lifetime. The resulting values would set the prioritization metric in terms of net present value for Caltrans to apply in selecting projects. The identification of an annual cost metric, which includes discounting based on federal- or state-identified discount rates, enables the important decision-making process on which project should advance given limited project resources. Table 4 highlights how the method would be implemented, with the project selected in the out years selected by the calculated annual cost metric. The impacts noted in the time period beyond the selected year (shown in shaded color) would be expected to have been addressed by the adaptation strategy. Thus, in the table, Project 1 at year 5 has the highest annual cost associated with disruptions connected to an extreme weather event. The project with the next greatest annual cost is Project 2, where this cost is reached at year 15. The next project is Project 3 at year 35 and the final project is Project 4 at year 45.

TABLE 4: EXAMPLE PROJECT PRIORITIZATION

Year	5	10	15	20	25	30	35	40	45	50
Project 1		$5	$5	$5	$7	$7	$7	$9	$9	$9
Project 2			$6	$6	$6	$6	$8	$8	$8	$8
Project 3								$8	$8	$8
Project 4									$10	$10

The project prioritization method outlined above requires the development of new approaches to determining how best to respond to climate change risks. It does not rely on existing methods as they are not appropriate to reflect climate risk effectively and facilitate agency level decision making. Climate change, with its uncertain timing and non-stationary weather/climate impacts, requires methods that incorporate this reality into Caltrans' decision-making processes.

It would be possible to implement a tiered prioritization process once work required to complete the steps as outlined above has been completed. Assets at risk from climate change with comparable present values could be compared for their capability to address other policy concerns – like goods movement, access for low income/dependent communities, sustainability measures, or other factors that would help Caltrans meet statewide policy goals. The primary focus of this assessment should be impacts to the system but these secondary measures can help clarify or reorder the final list and help guide implementation.

9. CONCLUSIONS AND NEXT STEPS

This report represents an initial effort to identify areas of exposure to potential climate change for facilities owned and operated by Caltrans District 8. The report included various data sources to identify how climatic conditions may change from today and where these areas of high exposure to future climate risks appear in District 8. The report presented the larger context of climate change down to a more localized understanding of what such change might mean to District 8 functions and operations, District 8 employees, and the users of the transportation system. It is intended, in part, as a transportation practitioner's reference for how to include climate change into transportation decision making in the context of a vulnerability assessment.

Much of today's engineering design is based on historical conditions, and it is emphasized throughout this report that this perspective should change. A review of climate data analyzed for this study shows that, for those stressors analyzed (SLR, storm surge, wildfire, temperature, and precipitation), there are clear indications that future conditions will be very different from today's, with likely higher risks to highway infrastructure. These likely future conditions vary in terms of when threshold values will occur (that is, when sea levels, or precipitation and temperature values exceed a point at which risks will increase for assets) and on the potential impact to the State Highway System. This is an important consideration given that transportation infrastructure investment decisions made today will have implications for decades to come given the long lifetimes for roadway facilities.

This report provides District 8 with the information on areas of climate change exposure it can utilize to proceed to more detailed, project-level assessments. In other words, the report has identified where climate change risks are possible in District 8 and where project development efforts for projects in these areas should consider changing future environmental conditions. There are several steps that can be taken to transition from a traditional project development process based on historical environmental conditions to one that incorporates a greater consideration for facility and system resiliency. This process can incorporate the benefits associated with climate change adaptation strategies and use climate data as a primary decision factor. District 8 staff has the capacity to adopt such an approach and ensure that travelers in the region are provided with a resilient system over the coming years.

The following section provides some context as to next steps for Caltrans, building upon this work and creating a more resilient State Highway System.

9.1. Next Steps

The work completed for this effort answers a few questions and raises many more. The scope of this work was focused on determining what is expected in the future and how that may affect the Caltrans SHS. This analysis has shown that climate data from many sources indicates an expanded set of future risks – from increased extreme precipitation, to higher temperatures, and an increase in wildfires – all concerns that will need to be considered by District 8.

There are a few steps that will be required to improve decision making and help Caltrans achieve a more resilient State Highway Network in District 8. These include:

- Policy Changes

  - Agency leadership will need to provide guidance for incorporating findings from this assessment into decision making. This area is a new focus and requires a different perspective that will not be possible without strong agency leadership.
    - Addressing climate change should be integrated throughout all functional areas and business processes; including Planning, Environmental, Design, Construction, Maintenance and Operations.
  - Risk-based decision-making. The changing elements of climate change require the consideration of the implications of those changes and how they may affect the system. Caltrans will need to change its methods to incorporate measures of loss, damage and broader social or economic costs as a part of its policies. (See 8.1 Risk-Based Design).
- Acquisition of Improved Data for Improved Decision-Making
  - Determining potential impacts of precipitation on the state highway system will require additional system/environmental data to complete a system-wide assessment. This includes:
    - Improved topographic data across District 8 (and the state of California).
    - Improved asset data – including accurate location of assets (bridges, culverts) and information on the waterway opening at those locations.
  - The assessment of wildfire potential along the state highway system is an ongoing effort. Follow up will be required to determine the results of new research and whether updated models indicate any additional areas of risk.
  - The precipitation and temperature data presented in this report is based off a data set that is newly released. Methods to summarize this data across many climate models is ongoing and the conclusions of that work may yield information that may more precisely define expected future changes for these stressors.
  - There are efforts underway to refine the understanding of other stressors, including landslide potential. Further refinements of those efforts will require additional investment and coordination to complete. Research efforts are constantly being refined and Caltrans will need to be an active partner in participating in, and monitoring, the results of these efforts to determine how to best incorporate the results of these efforts into agency practices.
- Implementation
  - The data presented in this report indicates directions and ranges of change. These data points will need to become a part of Caltrans practice for planning and design for all future activities.
  - The use of this data will require the development of educational materials and the training of Caltrans staff to ensure effective implementation.

Not every concern and future requirement could be addressed or outlined in this report. Thus, the report should be considered the first step of many that will be required to address the implications of climate change to the State Highway System. Much work remains to create a resilient State Highway System across California.

10. BIBLIOGRAPHY

Adaptation Clearinghouse. “California Executive Order S-13-08 Requiring State Adaptation Strategy.” Last accessed April 30, 2019. https://www.adaptationclearinghouse.org/resources/california-executive-order-s-13-08-requiring-state-adaptation-strategy.html

Bedsworth, Louise; Cayan, Dan; Franco, Guido; Fisher, Leah; Ziaja, Sonya. (California Governor’s Office of Planning and Research, Scripps Institution of Oceanography, California Energy Commission, California Public Utilities Commission). “Statewide Summary Report.” *California’s Fourth Climate Change Assessment*. Publication number: SUMCCCA4-2018-013. 2018. Retrieved from http://www.climateassessment.ca.gov/state/docs/20180827-StatewideSummary.pdf

California Air Resources Board. “Assembly Bill 32 Overview.” Last modified August 5, 2014. https://www.arb.ca.gov/cc/ab32/ab32.htm

California Legislative Information. “Assembly Bill No. 1482.” October 8, 2015. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1482

California Legislative Information. “Assembly Bill No. 2800.” September 24, 2016. http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2800

California Legislative Information. “Senate Bill No. 246.” October 8, 2015. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB246

Caltrans. “Highway Design Manual.” December 14, 2018. http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm

Caltrans. “Vulnerability Assessment.” Last accessed May 9, 2019. http://www.dot.ca.gov/transplanning/ocp/vulnerability-assessment.html

Crockett, Joseph and Westerling, Leroy. “Greater Temperature and Precipitation Extremes Intensify Western Us Droughts, Wildfire Severity, and Sierra Nevada Tree Mortality.” Journal of Climate 31(1):341-354. doi:10.1175/JCLI-D-17-0254.1 (2018). https://cloudfront.escholarship.org/dist/prd/content/qt3t39d8jq/qt3t39d8jq.pdf?t=osfbdf&v=lg

Federal Highway Administration (FHWA), “Adaptation Decision-Making Assessment Process.” Last modified January 12, 2018. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm

Gonzalez, P., G.M. Garfin, D.D. Breshears, K.M. Brooks, H.E. Brown, E.H. Elias, A. Gunasekara, N. Huntly, J.K. Maldonado, N.J. Mantua, H.G. Margolis, S. McAfee, B.R. Middleton, and B.H. Udall. “Southwest.” In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. *U.S. Global Change Research Program.* Washington, DC, USA, pp. 1101–1184. doi: 10.7930/NCA4.2018.CH25. https://nca2018.globalchange.gov/chapter/25/

Intergovernmental Panel on Climate Change (IPCC). “Representative Concentration Pathways.” Last accessed April 30, 2019. http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html

Intergovernmental Panel on Climate Change (IPCC). “What is a GCM?” Last accessed April 30, 2019. http://www.ipcc-data.org/guidelines/pages/gcm_guide.html

Keat, Mike. “Precast Concrete Speeds California Bridge Replacement.” American City & County. July 26, 2016. https://www.americancityandcounty.com/2016/07/26/precast-concrete-speeds-california-bridge-replacement/

KESQ. “Highway 74 Reopens After Landslide.” Last modified August 28, 2016. https://www.kesq.com/home/hwy-74-reopens-after-landslide/62498169

Maizlish, Neil; English, Dorette; Chan, Jacqueline; Dervin, Kathy; English, Paul. “Climate Change and Health Profile Report: Riverside County.” Office of Health Equity, California Department of Public Health. February 2017. https://www.cdph.ca.gov/Programs/OHE/CDPH%20Document%20Library/CHPRs/CHPR065Riverside__County2-23-17.pdf

Maizlish, Neil; English, Dorette; Chan, Jacqueline; Dervin, Kathy; English, Paul. “Climate Change and Health Profile Report: San Bernardino County,” Office of Health Equity, California Department of Public Health. 2017. https://www.cdph.ca.gov/Programs/OHE/CDPH%20Document%20Library/CHPRs/CHPR071SanBernardino_County2-23-17.pdf

Melillo, Jerry, Richmond, Terese (T.C.), and Yohe, Gary W. “Climate Change Impacts in the United States: The Third National Climate Assessment,” U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2. (2014)

National Oceanic and Atmospheric Administration. “Precipitation-Frequency Atlas of the United States.” 2018. https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume11.pdf

NBC Los Angeles. “Crews Gain Ground on Cottonwood Fire.” August 30, 2009. https://www.nbclosangeles.com/news/local/Crews-Gain-Ground-on-Cottonwood-Fire-56226382.html

Office of Governor Edmund Brown. “Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America.” Last modified April 29, 2015. https://www.ca.gov/archive/gov39/2015/04/29/news18938/

Tabbakhha, Maryam; Astaneh-Asl, Abolhassan and Setioso, Daniel Christian. “Failure Analysis of Flood Collapse of the Tex Wash Bridge.” University of California at Berkeley. *Proceedings of the World Congress on Civil, Structural, and Environmental Engineering.* Paper No. ICSENM 118 (2016): DOI: 10.11159/icsenm16.118, https://avestia.com/CSEE2016_Proceedings/files/paper/ICSENM/118.pdf

U.S. National Climate Assessment. “Extreme Weather." Accessed April 29, 2019. http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather

11. GLOSSARY

100-year design storm: Design criteria for infrastructure projects that address expected conditions for the 100-year storm. Considered Base Flood Elevation by the Federal Emergency Management Agency.

Cal-Adapt: A web-based data hub and information guide on recent California-focused climate data and analysis tools. Visualization tools are available to investigate different future climate scenarios.

Climate change: Change in climatic conditions due to the presence of higher greenhouse gas concentrations in the atmosphere. Examples include higher temperatures and sea level rise.

Downscaling: An approach to refine the outputs of global climate models to a more local level.

Emissions Scenarios: Multiple, long-term forecasts of greenhouse gases in the atmosphere based on global policy and economics.

Exposure: The degree to which a facility or asset is susceptible to climate stressors that might damage or disrupt the component.

Global Climate Model (GCM): Models used by climate scientists to project future, worldwide climate conditions. This term is sometimes used interchangeably with General Circulation Model.

Representative Concentration Pathways (RCP): A specific set of emission scenarios developed by the Intergovernmental Panel on Climate Change that project future concentrations of greenhouse gases in the atmosphere.

Resilient transportation facilities: Transportation facilities that are designed and operated to reduce the likelihood of disruption or damage due to changing weather conditions.

Stressor: Climate conditions that could cause negative impacts. Examples include higher temperatures or more volatile precipitation.

Vulnerability assessment: A study of areas likely to be exposed to future climate stressors and the consequence of that exposure.

This page intentionally left blank.