



# Sacramento Area Council of Governments

## *Project-Level Adaptation Strategies Guidance Document*

June 2020



## WHAT WE DO

The Sacramento Area Council of Governments (SACOG) is an association of local governments in the six-county Sacramento region. Its members include the counties of El Dorado, Placer, Sacramento, Sutter, Yolo, Yuba and the 22 cities within.

SACOG provides transportation planning and funding for the region and serves as a forum for the study and resolution of regional issues. In addition to preparing the region's long-range transportation plan, SACOG approves the distribution of affordable housing in the region and assists in planning for transit, bicycle networks, clean air and airport land uses.

*This assessment and its summary documentation were funded through a Senate Bill 1 Adaptation Planning Grant awarded by Caltrans in 2019. The views and opinions of the authors or agency expressed herein do not necessarily state or reflect those of Caltrans*

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## List of Acronyms and Abbreviations

ADAP	Adaptation Decision-Making Assessment Process
AADT	Average Annual Daily Traffic
ADT	Average Daily Traffic
BART	Bay Area Rapid Transit
CHAT	California Heat Assessment Tool
CMIP	Coupled Model Intercomparison Project
COGs	Councils of Government
CTA	Chicago Transit Authority
DOT	Department of Transportation
EO	Executive Order
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
GCM	Global Climate Model
GEV	Generalized Extreme Value
H&H	Hydrologic and Hydraulic
HHE	Heat Health Event
IDF	Intensity Duration Frequency
ITS	Intelligent Transportation System
LACMTA	Los Angeles County Metropolitan Transportation Authority
LHMP	Local Hazard Mitigation Plan
MARTA	Metropolitan Atlanta Rapid Transit Authority
MPOS	Metropolitan Planning Organizations
MTP/SCS	Metropolitan Transportation Plan/Sustainable Communities Strategy
OCS	Overhead Catenary System
O&M	Operations and Maintenance
OPC	Ocean Protection Council
OPR	Office of Planning and Research

PPA	Project Performance Assessment
ROW	Right of Way
SACOG	Sacramento Area Council of Governments
SacRT	Sacramento Regional Transit
SEPTA	Southeastern Pennsylvania Transportation Authority
TEACR	Transportation Engineering Approaches to Climate Resiliency
TMCs	Traffic Management Center
U.S. 50	U.S. Highway 50
UHI	Urban Heat Island
VHT	Vehicle Hours Travelled
VMT	Vehicle Miles Travelled
WCRP	World Climate Research Programme
ZST	Zero Stress Temperature

## Key Terminology and Definitions

Term	Definition
100-year storm or flood	A storm and associated flood event that has a 1 in 100, or 1%, chance of occurring in any given year.
Climate hazard/stressor	Negative outcomes and conditions from extreme weather, climate change, or other climate-related events (e.g. sea level rise, high heat event)
Consequence	Impacts from climate hazards or stressors, such as damage or disruption to a roadway.
Exposure/vulnerability	Areas of the transportation network that are likely to be affected by climate hazards (e.g. areas that are projected to flood in the future).
Likelihood	Probability of an event occurring, such as the chance of a storm event occurring in any given year.
Non-stationary	A condition that is subject to change over time. The term implies that past conditions are not necessarily valid in the future.
Risk	Function of likelihood and consequence.

## Introduction and Executive Summary

Under a changing climate, extreme weather events are projected to pose increasing risks to the transportation system. SACOG's *Vulnerability and Criticality Assessment* assessed these risks at a systems scale. This study, *Project-Level Climate Adaptation Strategies for Transportation in the SACOG Region*, focuses on the asset scale, examining risks facing individual transportation assets in greater detail and evaluating potential adaptation strategies.

This report provides guidance for transportation practitioners for addressing climate change risk at the project-level in the region and offers recommendations to SACOG for advancing the resilience of the region's transportation system.

Climate hazard resiliency is an area of growing emphasis at both the State and Federal levels. With the signing of Executive Order (EO) B-30-15 in 2015 and passage of Assembly Bill (AB) 2800 in 2016, State agencies and the projects they fund must take climate change impacts into account.

A major component of this study was to assess climate impacts and adaptation strategies for a few transportation projects representative of common project types in the region. These project-level assessments, or "representative projects," followed high-level guidance from the Office of Planning and Research document, *Planning and Investing for a Resilient California: A Guidebook for State Agencies*, which emphasizes the need for full lifecycle cost accounting when evaluating climate risk. The representative projects also used more detailed guidance from the Federal Highway Administration (FHWA) *Adaptation Decision-Making Assessment Process (ADAP)*. ADAP focuses on climate change assessments and decisions at the asset level.

These assessments offered lessons for future projects in the region, and in many cases, throughout the State. Some of the key recommendations and lessons from these project-level assessments are as follows:

- Strategies for addressing climate risk already exist; climate change requires a change in how strategies are evaluated and selected.
- Assessing lifecycle costs and cost effectiveness across multiple scenarios helps account for uncertainty in future conditions and enables identification of robust options that perform well across potential futures. Designing to a single one-size-fits-all hazard event does not adequately address this uncertainty.
- To make adequate adaptation decisions, information is needed on how different alternatives could fail due to climate hazards.
- Lifecycle costing should account for not only expected future damage costs, but also for disruption costs if an asset is unavailable for use.
- Timing is an important consideration. If risk is tolerable early in an asset's lifecycle and adaptation options are costly to implement, then it may make sense to monitor conditions and implement the action at a later point. However, agencies should be mindful of the potentially long duration of the project planning, design, and construction process and not delay addressing issues for too long.
- When projects involve the construction of new assets, there is an opportunity to address the climate risk in the design of the asset. The marginal costs of adapting a planned future asset to a climate-related risk are often relatively small compared to a baseline alternative that assumes the climate will remain the same in the future.

- As with other types of adaptation planning, cost-effectiveness should be considered alongside analysis of how options affect disadvantaged populations, greenhouse gas emissions, and other important regional considerations.
- Transit users may be disproportionately vulnerable to heat waves, especially if they are transit dependent, represent a heat-vulnerable population, and/or are waiting at tra during the hottest times of the day, and consideration should be given to how transit stops can be made more comfortable.
- Regular, proactive coordination between transportation design, transportation operations and maintenance (O&M), and emergency response professionals can improve infrastructure weaknesses and performance during evacuation events.
- Future flood conditions should be assessed in the hydrologic and hydraulic design of new assets. The future conditions could be exacerbated by sea level rise in the Delta and changing heavy precipitation patterns throughout the region, particularly in the mountainous areas.

The guidance provided in this report covers these lessons in more detail and discusses key considerations for major combinations of asset types and the climate hazards affecting them.

There are several ways for SACOG to implement the resiliency guidance into its activities. As SACOG does not directly manage transportation projects or systems, it can serve in a supporting role to its member counties and municipalities that do directly manage parts of the system. Support could include technical assistance on topics such as project-level climate projections, economic and risk analysis, and consequences of asset disruption on the overall transportation system. SACOG could also offer policy guidance and grant writing assistance to members.

SACOG can convene its members and other key regional stakeholders to collaborate on transportation resilience and help generate ideas or concepts for new projects that address climate risks at specific locations within the region. Furthermore, SACOG could integrate climate resilience into its current practices by considering climate risk when assessing project candidates for the regional flexible funding programs.

In addition to charting a path forward for climate resiliency in the SACOG region, the guidance and findings from this study are transferable to other parts of the State and can serve as helpful resource for Caltrans and other transportation practitioners.

## Project-level Guidance

### Purpose

The purpose of the Project-Level Guidance section is to provide a spectrum of tested methods and approaches that may be useful for other projects in the region.

### Organization of Project-Level Guidance

The Project-Level Guidance is separated into the following elements:

- **Federal and State Guidance** - This section presents State and Federal guidance for project-scale climate change adaptation strategies and summarizes a literature review conducted as part of this project.
  - This section also summarizes the FHWA ADAP federal framework applied in the project-level climate change and adaptation assessments completed for this effort.
- **Representative Projects** - This section compares methodologies that were applied in Task 1 and summarizes findings from the selected representative projects.
- **Economic Analysis for Project-Level Adaptation Planning** - This section focuses on the cost-benefit analyses and other economic comparison tools to evaluate adaptation strategies.
- **Implementation** - This section describes how future efforts can use this Project-Level Guidance to inform studies and projects like the representative projects analyzed.

## Federal and State Guidance

This section presents State and Federal policies and guidance that influence project-scale climate change adaptation strategies. It summarizes a literature review conducted before the project-level assessments began. Federal and California State policies and guidance documents were reviewed to understand what requirements and recommendations exist for integrating climate change risk into transportation projects. The review also identified any project-level frameworks that exist for assessing and addressing climate risk and similar project-level assessments for key takeaways. The findings from this literature review are summarized for each document reviewed at the state and federal levels.

FHWA's ADAP is summarized first below, as this process was applied by SACOG in the project-level assessments completed for this effort.

### Federal Guidance<sup>1</sup>

#### *Federal Highway Administration*

##### [FHWA's Adaptation Decision-Making Assessment Process](#)

FHWA's ADAP closely aligns with the needs of the SACOG project-scale pilots, as it is focused on guiding climate change assessments and decisions at the asset-level. It is built to account for increasing climate change risk in asset/facility design and can be applied to both existing and proposed projects (Federal Highway Administration 2019). The steps to the process are summarized below. See Figure for a decision tree of the ADAP steps.

1. **Understand the site context:** Understanding the site context is an important first step in assessing climate change impacts to a facility or asset. The site context includes the asset itself and its function within the transportation network, where it is located (including any site sensitivities or hazards), relevant policies and regulations, and who is involved (i.e. stakeholders and government agencies).
2. **Document existing or future base case facility:** ADAP can be used for both existing and proposed projects. For existing projects, this step involves documenting existing conditions and design. For proposed projects, this involved documenting the proposed design and relevant design standards.
3. **Identify climate stressors:** Next, document all the climate stressors that could affect the project. Depending upon the location, the site could be affected by multiple stressors at the same time. This step should also consider the compounding and combined effects of different stressors (i.e. sea level rise and precipitation). If there are no stressors that may affect the project, then the analysis is complete.
4. **Develop climate scenarios:** After identifying the stressors that may affect the project, identify climate data and scenarios that can be applied in the assessment. The data and associated scenarios should cover the design life of the facility and a range of potential outcomes. For example, multiple emissions concentrations pathways and models should

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<sup>1</sup> There is no currently applicable federal policy related to climate change adaptation.

be used to develop a range of climate change scenarios, including one or more high impact (or “worse case”) scenarios. Any number of climate scenarios can be generated, but normally the analysis will only need two to three scenarios (e.g. low, medium, high). Ensuring that there are at least a couple of scenarios to compare outcomes will allow for the consideration of various future possibilities and responses and will help to capture the range of uncertainty in projections. FHWA also notes that it may be helpful to maintain consistency across assumptions and timeframes for ease of comparison. Finally, it is important to consider how the stressors will affect the facility/asset on the ground. While some stressors may change over time, they may not have a direct impact to the project and therefore do not need to be evaluated.

5. **Assess performance of the facility:** Assess the performance of the facility, including under the *highest impact* scenario. If the facility/asset design criteria are met under this condition, aka there are no expected impacts from the scenario, the analysis is complete. If there are expected impacts, then the additional scenarios established in Step 4 should also be assessed.
6. **Develop adaptation options:** If the cost to adapt to the highest impact scenario is relatively low, then adapt to that scenario and the analysis skips to Step 9. If the cost to adapt is relatively high, then develop adaptation options for the other scenarios assessed.<sup>2</sup>
7. **Assess performance of the adaptation options:** Next, the performance of each adaptation option should be assessed against each climate scenario. This will help identify the effectiveness of different adaptation options and which climate stressors/scenarios they protect against. There may be multiple adaptation options for each climate stressor or there may be cases where there are fewer options due to fewer climate stressors and associated impacts. At this stage, it is helpful to begin to collect information about the cost of different options.
8. **Conduct an economic analysis:** The economic analysis is one of the most important aspects of decision-making, especially as transportation projects are often limited by existing budgets and funding. A benefit-cost analysis can be used here as a tool to understand the relative costs and benefits of each adaptation option, including avoided costs that would have otherwise been incurred due to climate change impacts.
9. **Evaluate additional considerations:** While cost is an important consideration when choosing an adaptation strategy, there are many other factors that should be weighed when making a final decision. Many of these other variables are introduced in Step 1: “Understand the site context” and include things like: environmentally sensitive areas, stakeholder input, affected underserved, vulnerable, and/or disadvantaged populations, and policy considerations.
10. **Select a course of action:** Finally, the information compiled above can be used to decide which adaptation strategies to apply. Some can even be applied during the facility/asset operations and would be implemented later in the design life.

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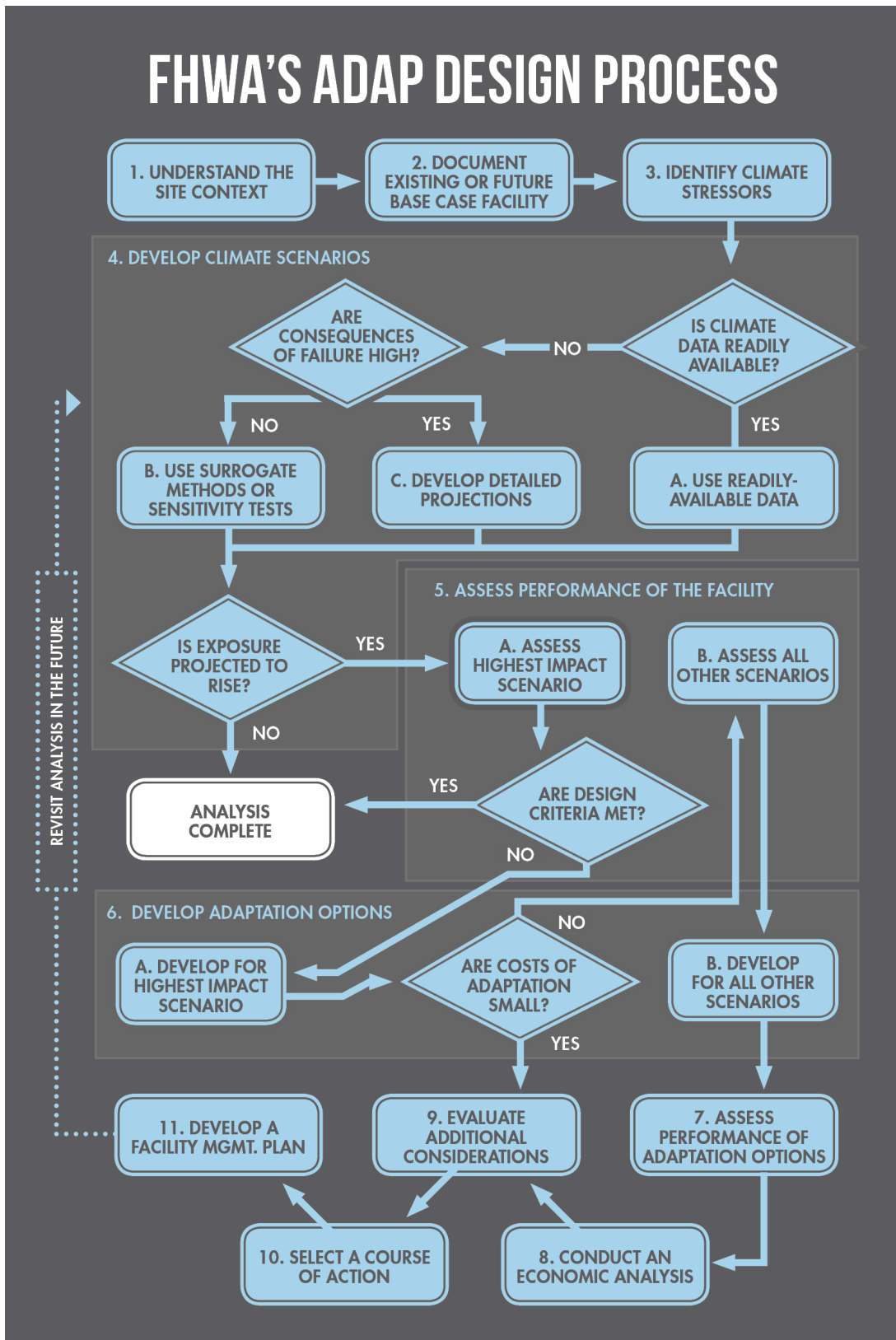
<sup>2</sup> Steps 5 & 6 are often done in conjunction.

11. **Develop a facility management plan:** And last, a facility management plan should be developed so the adaptation strategies applied are properly maintained and monitored. Other strategies that are planned for implementation later in the facility/asset design life should be documented here.

While not an official ADAP step, it may also be relevant to revisit the analysis in the future, if new climate data or information becomes available, changes are made to the facility/asset or the project site, and/or technical advancements make new adaptation strategies plausible options.

**FHWA's ADAP was applied in the SACOG project-level pilot studies, given the relevance of the guidance to the effort. These steps were followed at a higher level for some of the pilot projects, but the overall structure of the assessments remained consistent with ADAP.**

Figure 1. ADAP Steps



### Vulnerability Assessment and Adaptation Framework (3<sup>rd</sup> Edition)

The Federal Highway Administration (FHWA) developed the *Vulnerability Assessment and Adaptation Framework* (3<sup>rd</sup> edition) to help state Departments of Transportation (DOT), Metropolitan Planning Organizations (MPOs), and other transportation agencies assess the impacts of extreme weather and climate change to the infrastructure they manage (Federal Highway Administration 2017). At a high-level, the framework outlines the following steps:

1. **Define study scope:** Consider the study objectives and end goals when deciding upon the scope. Select relevant assets, climate stressors, and stakeholders. Where data is available, conduct a criticality assessment to better understand the status of the region's most important assets.
2. **Gather asset data:** Identify the range of asset data available and work within the bounds of what is accessible. Consider opportunities to collect new data where information does not currently exist.
3. **Gather climate data:** Collect projections through coordination with partners. Use best available, existing resources, or develop new data where information is unavailable for the study area. The climate stressor under consideration determines the approach to collecting climate data:
  - a. **Temperature and precipitation:** Practitioners can 1) use existing data and general trends on regional change, 2) use existing downscaled data, 3) develop projections tailored to study needs.
  - b. **Riverine hydrology:** Apply FHWA's Hydraulic Engineering Circular No. 17, 2nd Edition (HEC-17) level of analysis appropriate to the project and study area (HEC-17 is summarized below).
  - c. **Sea level rise:** Apply FHWA's [Highways in the Coastal Environment, Hydraulic Engineering Circular No. 25 – Volume 2 \(HEC 25\)](#) to calculate future projected sea level rise at the study area. Use the best available science.
  - d. **Storm surge:** Apply HEC 25, which provides guidance on methodologies for assessing exposure of infrastructure to storm surge. As with HEC 15, multiple levels of analysis are provided, which take varying degrees of effort.
4. **Assess vulnerability:** Vulnerability is a function of the transportation system's exposure to climate stressors, sensitivity to those impacts, and adaptive capacity, or ability to change in response to those impacts. Assess through one of three approaches:
  - a. **Stakeholder Input Approach:** Rely on institutional knowledge to assess vulnerabilities to the system. Hold workshops to discuss asset exposure and weigh the most critical assets and significant risks.
  - b. **Indicator-Based Desk Review Approach:** Score and rank vulnerable transportation assets based upon existing data. Convert rankings to a single score for each asset and climate stressor considered. Can be combined with stakeholder input approach.
  - c. **Engineering-Informed Assessments:** Asset-specific analyses that rely on design information to assess impacts and evaluate adaptation options.
5. **Identify, analyze, and prioritize adaptation options:** Study a range of affected assets and begin to consider applicable adaptation options. Consider monetary impacts as well as those that cannot be quantified (e.g. community benefits). Use economic analyses to

evaluate options.

6. **Incorporate assessment results in decisions:** Incorporate results into transportation planning and future projects. Monitor adaptation strategies in place and consider future modifications as necessary.

The SACOG *Vulnerability and Criticality Assessment* accomplished steps 1 – 3 above and applied elements of 4a and 4b. SACOG's project-scale assessments accomplish step 4c above. The project-scale assessments also evaluated potential adaptation options, per step 5 above. To date, the work SACOG has completed aligns closely with Federal guidance. Moving forward, the FHWA framework can be helpful to guide adaptation decisions and move SACOG toward step 6.

### Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets

FHWA also produced a guidance document on incorporating considerations of climate change and risk management into asset management. The report notes that while asset management is not a "silver bullet" solution to climate change adaptation, it can help a transportation agency increase their system redundancy, robustness, and resiliency to ultimately create a stronger transportation system. The report notes that asset management can contribute to overall system resiliency and climate change-preparedness in the following ways:

1. Providing accurate asset inventories and their conditions,
2. Instituting maintenance practices,
3. Prioritizing critical assets,
4. Planning for different scenarios and post-event recovery,
5. Mapping assets geospatially and using this information to coordinate evacuation planning,
6. Developing accurate inventories of roadway signage and traffic control devices for use in an emergency, and
7. Planning for pre-event coordination and post-event recovery.

Forward-looking asset management practices will not only ensure that assets are protected and well-maintained in the face of a changing climate, they will provide important data needed for climate change vulnerability assessments. Many transportation agencies lack up-to-date data on their asset inventories, locations, conditions, and lifespans. This information is especially helpful for detailed and site-specific assessments of assets and their vulnerability to climate stressors, as well as for planning replacement/maintenance cycles and preparing for disasters (Federal Highway Administration 2013). For these reasons, FHWA encourages that climate change planning is incorporated into asset management practices.

### Transportation Engineering Approaches to Climate Resiliency (TEACR) Studies

After developing ADAP, FHWA applied the approach through several pilot studies (ADAP is covered above). These Transportation Engineering Approaches to Climate Resiliency (TEACR) studies assessed a range of climate stressors and facilities/assets (Federal Highway Administration 2019). Stressors included sea level rise and storm surge, temperature rise, precipitation change and riverine flooding, and wildfire risk. Transportation assets evaluated included: bridges, culverts, a living shoreline, and roadways. One of the studies compared economic analyses methodologies and their assumptions for use in ADAP. These studies provide useful examples of how ADAP is applied and can serve as references for SACOG's own project-

level assessments.

The study's final summary report, *Synthesis of Approaches for Addressing Resilience in Project Development*, provides overarching lessons learned through the project-level pilot studies. These lessons learned are broken up into the following categories:

1. Scoping asset-level adaptation assessments,
2. Applying climate science and managing uncertainty,
3. Integrating climate and weather risks into asset management,
4. Breaking down silos,
5. Selecting and implementing adaptation measures,
6. Understanding conservatism in design assumptions, and
7. Considering the big picture.

The overarching lessons learned from TEACR are summarized in Table 6 of the FHWA summary report (Federal Highway Administration 2017). SACOG may choose to review these lessons learned for consideration in their own climate change assessment and adaptation activities. The pilot projects themselves also provide useful examples of how to conduct a project-level assessment of climate change impacts.

### Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience

FHWA's Hydraulic Engineering Circular No. 17, 2<sup>nd</sup> Edition (HEC 17) manual provides specific technical guidance on how to assess riverine flood impacts to highway system infrastructure. The focus of the manual is on "describing exposure to extreme riverine flooding in the context of changing conditions. The manual specifically addresses climate change as one source of change that potentially affects the magnitude and frequency of extreme events that, in turn, may affect transportation assets" (Federal Highway Administration 2016). The manual's eight sections provide guidance on how to address non-stationarity<sup>3</sup> and future conditions.

- Section 1 provides general background information and the purpose and need for this manual.
- Section 2 provides background on floodplain management and FHWA's floodplain policies.
- Section 3 summarizes methods used to estimate riverine flood events, including: how to estimate flood discharge, how to apply rainfall and runoff models, and how to develop appropriate extreme flood events.
- Section 4 includes information on non-stationarity and how to adjust for diversions from historical records.
- Section 5 details climate models and how to use their outputs.
- Section 6 focuses on evaluating risk, especially as it relates to design criteria exceedance and infrastructure damages, and how to reduce that risk/increase resiliency.

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<sup>3</sup> A non-stationary condition is one that is subject to change over time. Non-stationarity implies that past conditions are not necessarily valid in the future. The climate is an example of a non-stationary system.

- Section 7 provides a framework for assessing riverine flooding impacts to highway infrastructure.

The framework recognizes that different projects may require different levels of analysis, so it is broken into 5 levels of detail:

1. **Historical discharges:** Use standard hydrological techniques based on historic information and qualitatively consider climate change and changes to land use.
2. **Historical discharges/confidence limits:** Complete level 1 and then quantitatively estimate a range of confidence limits for discharge based upon historic data.
3. **Historical discharges/confidence limits with precipitation projections:** Complete level 2 and quantitatively estimate projected changes in precipitation for the site. Determine if design changes are needed based upon precipitation projections.
4. **Projected discharges/confidence limits:** Complete level 3 and perform hydrologic modeling using projected land use and climate data to estimate projected design discharges and confidence limits.
5. **Projected discharges/confidence limits with expanded evaluation:** Complete level 4 and broaden the analysis to include experts in the field of climate science and/or land use planning to ensure site-specific projections are vetted and approved.

For all levels of analysis except for level 1, FHWA suggests applying confidence limits to account for uncertainty in hydrologic analyses. These confidence intervals increase over time because the project/asset must be in place for longer. The proposed confidence intervals based on hydrologic service life are summarized in Table 1 (Federal Highway Administration 2016).

HYDROLOGIC SERVICE LIFE (YEARS)	CONFIDENCE INTERVAL
Less than 30	38%
Between 30 and 75	68%
Greater than 75	90%

*Table 1. Confidence Intervals Based on Hydrological Service Life*

On how to apply these confidence intervals, the manual states “The general approach for application of confidence limits described in this manual for analyses beyond level 1 is to identify the sources of model and data uncertainty and use that variation to quantify a reasonable range of flow conditions over which to evaluate and design plans and projects to increase their resilience” (Federal Highway Administration 2016).

FHWA also provides recommendations for Global Climate Model (GCM) projections and emissions scenarios to use in these assessments. Specifically, FHWA recommends using World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP5) data and middle to above-middle emissions scenarios (RCP 6.0).

SACOG’s can apply one of the HEC-17 levels of assessment as outlined above for any facilities/assets that may face impacts of riverine flooding.<sup>4</sup> The level of assessment chosen

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<sup>4</sup> More detail on each level of assessment is available in the manual.

depends upon resources available.

### *Federal Transit Administration*

#### [Transit and Climate Change Adaptation: Pilot Projects](#)

In 2011, the Federal Transit Administration (FTA) committed one million dollars to funding seven pilot climate change research efforts around the nation. The pilot projects and involved transit agencies included:

- An Integrated Approach to Climate Adaptation at the Chicago Transit Authority (CTA)
- A Vulnerability and Risk Assessment of the Southeastern Pennsylvania Transportation Authority's (SEPTA's) Regional Rail
- Gulf Coast Climate Change Adaptation Pilot Study
- Los Angeles County Metropolitan Transportation Authority (LACMTA) Climate Change Adaptation Pilot Project Report
- San Francisco Bay Area Rapid Transit District (BART) Climate Change Adaptation Assessment
- Sound Transit Climate Risk Reduction Project
- Transit Climate Change Adaptation Assessment/Asset Management Pilot for the Metropolitan Atlanta Rapid Transit Authority (MARTA)

Each of the pilot studies focused on identifying the relevant climate stressors for that geography, the potential transit impacts to the transit system, and the set of feasible adaptation strategies for the system. The synthesis report completed for the seven pilots identified that while climate stressors varied across geographies, the trends in projections were similar, as were the expected impacts to the transportation system. A list of general adaptation strategies was collected across all pilots, which is summarized on pages two and three of the synthesis reports (Federal Transit Administration 2014).

### [California State Policy](#)

#### *Executive Order B-30-15*

Signed in 2015 by Governor Brown, [Executive Order \(EO\) B-30-15](#) requires the consideration of climate change in all state investment decisions. This order was the first to require state agencies to consider the impacts of climate change on their projects. It went a step beyond previous orders and legislation related to climate change, which were all focused on greenhouse gas emissions reductions. The EO expands on this requirement by specifying that state agencies should:

- Use full life cycle cost accounting when planning adaptation,
- Prioritize adaptation actions that also reduce greenhouse gases,
- Consider the state's most vulnerable populations,
- Prioritize natural infrastructure solutions, and
- Use flexible approaches where possible to avoid maladaptation.

### *Senate Bill 379*

Also signed in 2015, [SB 379](#) requires that upon the next revision of a General Plan the safety element will address climate change adaptation and resiliency strategies applicable to the city or county. This review and update must include the following:

- A vulnerability assessment, which identifies relevant climate change risks,
- A set of adaptation and resilience goals, policies, and objectives based upon the findings of the vulnerability assessment.
- A set of feasible responses and strategies that will help the jurisdiction meet the goals, policies, and objectives set based upon the vulnerability assessment findings. These objectives may include:
  - Methods to avoid climate risks, associated with new land uses,
  - Relocation of essential public facilities (e.g. hospitals, emergency shelters, emergency command centers) to avoid climate risks,
  - Careful designation of infrastructure in at-risk areas (i.e. only place infrastructure that is resilient against these risks in these locations),
  - Plans and guidelines for stakeholder collaboration to address risks,
  - Opportunities to apply natural infrastructure solutions, wherever possible.

If cities and counties have a Climate Adaptation Plan or Local Hazard Mitigation Plan (LHMP) that contains the elements required above, then they may use these documents to comply with SB 379 (they must incorporate them by reference into the safety element of their General Plan).

### *Assembly Bill 2800*

Assembly Bill 2800 was approved in 2016 and requires state agencies to take climate change impacts into account during all infrastructure planning, design, construction, investments, operations and maintenance. The bill also required the formation of a Climate-Safe Infrastructure Working Group made up of engineers and architects with relevant experience in infrastructure and climate change mitigation and adaptation. This working group created *Paying it Forward: The Path Toward Climate-Safe Infrastructure in California*. See below for more on this guidance document and its recommendations.

### *Senate Bill 1035*

[SB 1035](#) (2018) requires that General Plan safety elements are:

- Reviewed and revised to include climate adaptation and resiliency strategies, as necessary,
- Reviewed by the planning agency,
- Updated every time the housing element or LHMP is updated, or at least every 8 years, and
- Prepared with best available information related to flood, fire hazards, and climate change.

The legislation will ultimately ensure that new information is incorporated into the General Plan as required by SB 379.

## California State Guidance

### *Office of Planning and Research*

#### Planning and Investing for a Resilient California

EO B-30-15 (see above) initiated the development of a Technical Advisory Group led by the Office of Planning and Research, who developed a guidebook for state agencies to respond to the order. The guidance document, *Planning and Investing for a Resilient California: A Guidebook for State Agencies*, outlined a general process for state agencies to follow to assess and address climate change risks. Generally, this guidebook recommends that state agencies identify how climate change could affect a project or plan, conduct an analysis of climate risks, make a climate-informed decision, and track and monitor progress. The guidebook also provides suggestions related to developing an assessment methodology (in Step 2 of the report) and recommends that climate risk analyses (Governor's Office of Planning and Research 2018):

1. Use a large variety of GCMs,
2. Use multiple emission scenarios if considering impacts after 2050 (use only RCP 8.5 if considering impacts before mid-century),
3. Use up-to-date or "best available" information,
4. Use downscaled data,
5. Assess sea level rise, and
6. Consider a worst-case scenario.

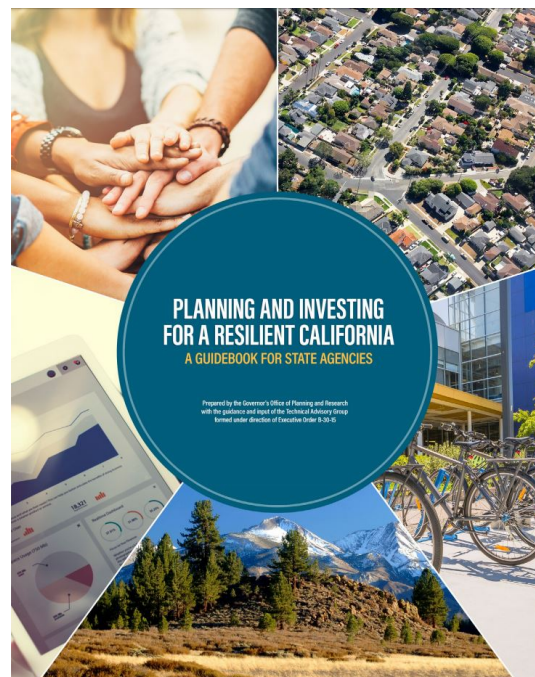
The EO requirements are important considerations for developing adaptation options. The full life cycle cost accounting can be incorporated into economic analyses completed for any adaptation option and fits into Step 8 of ADAP. The other considerations (consider vulnerable populations, use flexible approaches) can be incorporated into Steps 6 and 9, when adaptation options are developed, and other considerations are evaluated.

The *Planning and Investing for a Resilient California* guidance on climate change assessments can also be considered in the project-level studies and incorporated into ADAP. They are especially relevant to Step 4 of ADAP, where climate scenarios are first developed.

SACOG applied the general principles of the EO requirements and the *Planning and Investing for a Resilient California* guidance to the representative projects assessed for this effort.

#### General Plan Guidelines: 2017 Update

SB 379 (see above) requires that upon the next revision of a jurisdiction's General Plan on or after January 1st, 2017 (or if a local jurisdiction has not yet adopted a plan on or before January 1st, 2022), the safety element will be reviewed and updated to address climate change adaptation and resiliency strategies applicable to the city or county. In response to the SB, the Governor's



Office of Planning and Research updated the state's General Plan Guidelines, which now requires that a new climate change section be added within each General Plan safety chapter, and its inclusion is encouraged in other chapters as well. The safety chapter must address community vulnerabilities, create a set of goals, policies, and objectives for reducing greenhouse gas emissions, and identify a set of feasible implementation measures for greenhouse gas reduction and adaptation strategies.

An entire chapter on climate change was added to the guidelines, which also provides guidance on CEQA streamlining and greenhouse gas reduction plans. See Chapter 8 of the Office of Planning and Research's General Plan Guidelines: 2017 Update for more information (Governor's Office of Planning and Research 2017).

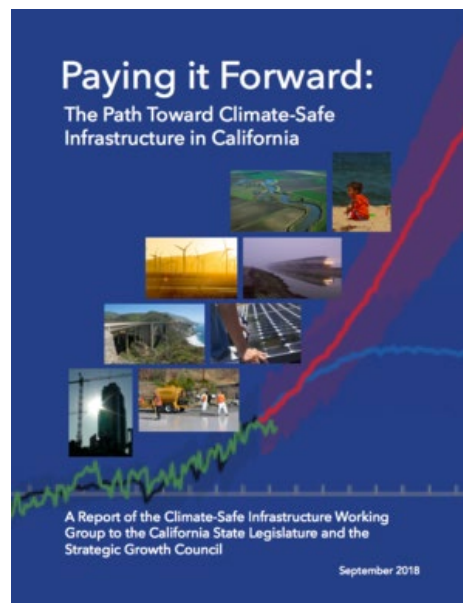
The General Plan Guidelines update creates an opportunity for SACOG to collaborate with its members on climate change vulnerability, safety issues, and adaptation strategies. SACOG has identified climate change risks and adaptation responses through its *Vulnerability and Criticality Assessment* and representative projects, which could be incorporated into its member's General Plans.

### *Climate Safe Working Group*

#### [Paying it Forward: The Path Toward Climate-Safe Infrastructure in California](#)

*Paying it Forward: The Path Toward Climate-Safe Infrastructure in California* outlines ten recommendations for legislators, engineers, architects, scientists, consultants, and other stakeholders to develop climate-ready infrastructure for California (Climate-Safe Infrastructure Working Group 2018):

1. The State Legislature should establish "The Climate-Safe Path for All" as official state policy, which accounts for the full lifecycle cost of infrastructure, uses a multi-sectoral approach, and prioritizes infrastructure investments in the state's most disadvantaged populations.
2. The State Legislature should provide a permanent funding source for the state's Climate Change Assessment, [the Climate Change Research Program](#), and other tools and assistance agencies need to assess and respond to climate change.
3. The state budget should provide funding to state infrastructure agencies so their engineers and architects can research solutions to climate change.
4. The state budget should improve staff capacity and increase project funding to better address uncertainties inherent in planning for future climate change and the costs associated with those changes.
5. Engage all affected stakeholders in infrastructure planning and decision-making.



6. State agencies should update their infrastructure standards, codes, and guidelines that are dependent upon climate and/or weather data to create more future-oriented designs.
7. The state should help policymakers and the public understand the additional upfront costs of planning for climate change adaptation and why it is necessary.
8. The Strategic Growth Council should work with the Government Operations Agency, Labor and Workforce Development Agency, and other relevant agencies to create a plan for training the infrastructure delivery workforce on the impacts and science of climate change.
9. The state should establish a standing Climate-Safe Infrastructure Working Group.
10. The state budget should provide full funding to agencies to respond to climate change in infrastructure delivery.

Most of these recommendations apply to the State Legislature or state agencies, and do not directly apply to SACOG. SACOG may be affected by future changes to legislation, policy, or infrastructure standards, codes, and guidelines, that are developed in response to the Climate-Safe Infrastructure Working Group's suggestions.

### *Caltrans*

#### [Addressing Climate Change Adaptation in Regional Transportation Plans](#)

Caltrans has existing guidance on climate change planning for Councils of Government (COGs), such as the *Addressing Climate Change Adaptation in Regional Transportation Plans* report, which was developed as a guide for California MPOs and Regional Transportation Planning Authorities (RTPAs). This guidance outlines two approaches for MPOs and RTPAs to assess climate change impacts to their transportation networks: a basic and advanced approach.

The report provides a high-level framework for assessing climate change risks, then provides more detail on how to integrate adaptation planning into regional transportation plans, for more advanced MPOs. The high-level evaluation approach suggests the MPO "(1) assess potential climate effects in the MPO's region; (2) consider the impacts of climate change on the MPO's five key transportation assets; and (3) develop a short list of adaptation strategies" (Caltrans 2013). The more advanced approach for adaptation planning is provided in Part III of the report, and involves assembling an asset inventory, determining criticality, and assessing vulnerability to key assets. After this assessment process, the MPO would prioritize the most critical and vulnerable assets for adaptation (Caltrans 2013).



### Caltrans Climate Change Vulnerability Assessment

In 2016, the Caltrans Climate Change Branch began the agency's first complete climate change assessment of the State Highway System. The *Caltrans Climate Change Vulnerability Assessment* was conducted to identify segments of the highway system that could be affected by climate stressors over the coming century. An assessment was completed for each of the 12 Caltrans districts to assess highway vulnerabilities to stressors including: temperature rise, precipitation change, wildfire risk, sea level rise, storm surge, and cliff retreat.

The district-level assessments identified portions of regional highways that may be at risk from these hazards over multiple time horizons and scenarios. The data and information were provided to district staff to help them identify relevant climate risks in their district, assets that are more vulnerable than others, and planning-level responses. This statewide effort influenced regional assessments that followed, including SACOG's *Vulnerability and Criticality* assessment.

### Caltrans Climate Action Reports

As the next phase of their work, Caltrans is expanding upon their vulnerability assessment findings through another effort called the Caltrans Climate Action Reports. As part of this project, Caltrans is using vulnerability assessment data to apply an indicator-based approach to prioritize its most vulnerable assets for further review and adaptation. Factors that influence the prioritization include exposure to different climate hazards, Average Daily Traffic (ADT), and average detour time around a failed asset. These reports are intended primarily for internal use to help districts identify their most critical and vulnerable assets, which then would undergo site-specific assessments through an ADAP-style approach to identify adaptation alternatives.

In addition, Caltrans is developing another internal report that will provide a set of recommendations for the agency to incorporate climate change adaptation planning into day-to-day agency practices. This *Caltrans Adaptation Strategy Report* will include engineering-level recommendations as well as procedural/policy related strategies.

## Representative Projects

Following the completion of SACOG's *Vulnerability and Criticality Assessment* and the literature review outlined above, SACOG selected representative projects from the Metropolitan Transportation Plan/Sustainable Communities Strategy (MTP/SCS) as well as some hypothetical project examples for project-level climate change assessments. These representative projects demonstrate a range of project and asset types, and different climate hazards that will affect the region's transportation network. FHWA's ADAP steps were used to guide these project-level assessments and so they included the assessment of future climate scenarios, evaluation of different adaptation options, varying degrees of economic analysis, and a set of recommendations for each project. These representative projects provide examples for SACOG and its member agencies which can be used to guide similar assessments in the future. The representative projects demonstrate the following principles:

- How to use FHWA's ADAP to guide project-level climate change assessments,
- How to modify project-level assessments based on assets and hazards reviewed,
- How to develop and review adaptation options,
- How to compare cost-effectiveness of different adaptation options,
- How to holistically review variables that affect decision-making and account for uncertainty,
- And how to develop a set of responses at the asset-level.

The representative projects are summarized below, along with any key lessons learned and recommendations for similar studies. Also see the

Economic Analysis for Project-Level Adaptation Planning and Guidance Implementation sections for more information on how to approach similar types of project-level assessments.

## Extreme Heat and Transit Stop Pilot

### Summary

This pilot analyzed the impacts of extreme heat to transit users at a bus stop in Rancho Cordova in Sacramento County, as shown Figure 2. The case study uses the ADAP steps to exemplify possible decision-making processes and compare costs and benefits of different adaptation alternatives.

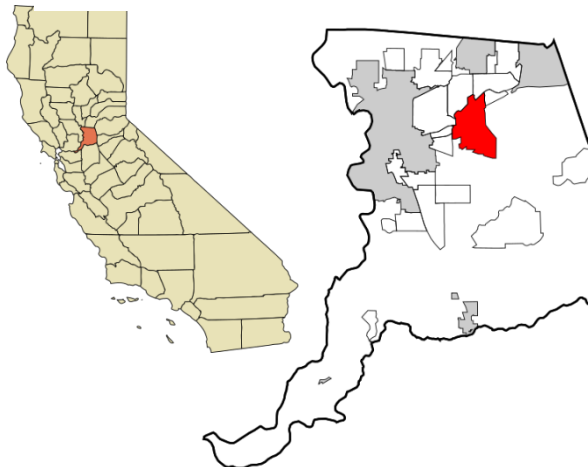
The bus stop selected for analysis is the Zinfandel Plaza stop (#658), at Zinfandel Drive and Ross Parking Lot in Rancho Cordova. Rancho Cordova is situated in northeastern Sacramento County, approximately 20 to 30 minutes east of downtown Sacramento. A community survey completed for the [Capital Region Urban Heat Island \(UHI\) Mitigation Project](#) collected information on community priorities around the Capital Region related to heat vulnerability. The Zinfandel Plaza stop was selected following a review of 30 bus stops where survey results reported a lack of shade, benches, and other forms of shelter. The bus stop currently has a single shade canopy but does not have shade options available outside of this small shelter. The stop is also in the middle of a parking lot and idling vehicles could additionally exacerbate heat pollution in this area.

The study reviewed existing conditions at the site, including population characteristics, site conditions, and bus operations. Next, the study compiled and reviewed future changes in temperature, extreme heat, and the Urban Heat Island (UHI) effect at the site. Temperature data was compiled from the past SACOG *Vulnerability and Criticality Assessment*, the California Heat Assessment Tool (CHAT), and the *Capital Region UHI Mitigation Project*. The study attempted to assess the performance of the facility under current temperature conditions, but this was challenging given limited data and resources to quantify performance. The study also qualitatively discussed potential impacts to ridership and revenue due to temperature rise, but this was also difficult to quantify.

In addition, the study compiled a shortlist of potential adaptation measures to apply at the Zinfandel stop, along with information surrounding their effectiveness, costs, co-benefits, and challenges. The most cost-effective options were identified based upon this information, but an economic analysis was not performed. Finally, the study evaluated additional considerations at the site and presented a set of recommended approaches to adaptation. Given available information, we recommend that Sacramento Regional Transit (SacRT) and SACOG consider the following strategies to reduce exposure to Heat Health Events (HHEs) at Zinfandel Plaza:

- Install a water fountain
- Install a high-pressure water mister

Figure 2. Map of Rancho Cordova in Sacramento County



Source: Map by Arkyan, [creative commons license](#).

- Install a cool wall shelter
- Develop a list of shade trees adapted to future climate through a partnership with the Sacramento Tree Foundation

SacRT and SACOG may also want to consider:

- Installing benches
- Planting shade trees
- Installing permeable/green pavement at the site (could be on the concrete pad the shelter sits on)

### *Lessons Learned/Considerations for Similar Assessments*

- This assessment was different than the "typical" ADAP assessment because it focused exclusively on impacts to riders, not a piece of infrastructure. Conducting this assessment took some flexibility.
  - Changed some of the approaches to the ADAP steps:
    - During Steps 1 and 2 it was important to consider how a rider would experience the bus stop. This information cannot be collected by looking at designs and blueprints, but by examining population characteristics, ridership, location, etc.
    - Step 5 was not possible with the information available. More information was needed on how the public experiences the stop and would need to conduct some follow-up surveys to collect feedback on adaptation measures.
    - Steps 7 and 8 changed somewhat as there are many combinations of adaptation measures that could be applied to reduce heat stress to riders. Not just one or two. It did not seem appropriate to narrow down to 1-2 concrete suggestions.
      - The study provided several recommendations and scenarios for applying them.
      - The cost-effectiveness of these measures may be hard to quantify in an economic analysis.
    - The facility management plan (Step 11) is also non-traditional. It instead needs to focus on maintenance requirements and monitoring the performance of adaptation measures through performance indicators like customer satisfaction.
- There were many additional considerations to include in Step 9, especially when dealing with impacts to public health. Disadvantaged/heat-vulnerable communities are a major consideration. Rider acceptance of an adaptation option (e.g., additional shading) is important, because the ridership is likely to experience that adaptation option directly and tangibly.

### *Key Takeaways*

- Temperatures are rising across the SACOG region and the number of HHEs and overall public health impacts are expected to increase.
- Transit users may be disproportionately vulnerable, especially if they are transit dependent, represent a heat vulnerable population, and/or are waiting for their bus during the hottest times of the day (as they would at this stop).
- Collecting rider feedback is an important way to understand current site conditions, develop goals for the site, and evaluate performance after making changes.
- There are many options available to reduce heat impacts at bus stops. In addition, local/regional policies and goals are supportive of reducing heat pollution and impacts. The challenges tend to lie with implementation (permitting, ADA compliance, construction, maintenance, utility access, etc.). These barriers can be significant for transit agencies and will need to be addressed/removed to move forward with adaptation measures.

## Extreme Heat and Pavement

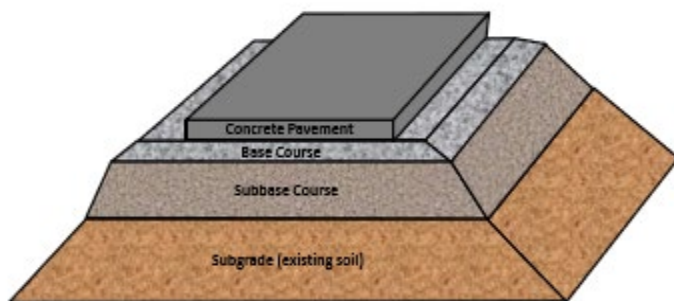
### *Summary*

This case study is a theoretical example of assessing the performance grade binder for an asphalt roadway under increasing heat stress due to climate change. Asphalt pavement is generally built over a base and subbase course, usually a gravel or stone material, as shown on Figure 3.<sup>5</sup> The sublayers provide foundational support to prevent the pavement from becoming deformed from the vehicles loads. The asphalt binding agent in a roadway is essentially the "cement" that keeps the aggregate together. The performance grade (PG) asphalt binder choice is determined by the 7-day maximum pavement temperature (°C) and 1-day minimum pavement temperature (°C) values (i.e., annotated as: PG ##H - ##L [where ##H relates to high pavement design temperature under an average 7-day maximum and is intended to protect against rutting and shoving, and ##L relates to low pavement design temperature for the 1 day minimum and is intended to protect against thermal cracking]).

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<sup>5</sup> A course is a material layer. Combining all the layers creates the pavement structure.

Figure 3. Illustration of Roadway Layers



Source: (Federal Highway Administration 2017)

Under a changing climate, the appropriate performance binder grade shifts from PG 64-10 to PG 70-10 over the coming century. The timing of that shift depends on the climate scenario and the road location within the SACOG region. A moderate future warming suggests this change may occur around 2065, whereas a more extreme future warming suggests this change may occur around 2040. Both futures are plausible and depend on how society evolves over the coming century.

Recent studies were reviewed for relationships that described the accelerated loss of asphalt performance in response to a PG rating lower than its environmental exposure (e.g., PG 64-10 in an environmental setting that recommends a PG 70-10). This study relies on recent work that suggests an accelerated performance loss of 10% for interstates and 15% for national, state, and local routes when using the wrong asphalt grade. In response to the accelerated degradation of the integrity of the pavement, this study calculated and compared the lifecycle costs in maintenance and rehabilitation under today's conditions and under both future scenario conditions. Using a real discount rate of 4%, this study found an increase in lifecycle costs of \$3,576 for the moderate future scenario up to \$42,126 for the more extreme future warming scenario, compared to present-day estimates of a static climate. Note that applying a discount rate dramatically decreases future maintenance and rehabilitation costs, reducing the monetized impacts associated with future conditions.

This study assessed 3 adaptation options:

1. Use a PG 70-10 performance binder grade at the onset of constructing the road,
2. Replace the PG 64-10 pavement with PG 70-10 during rehabilitation, and
3. Significantly increase maintenance and inspection.

Under a moderate future warming scenario, option 2 suggests a reduction in lifecycle costs of \$23,466, and option 3 suggests a reduction in lifecycle costs of \$76,589 compared to no intervention. Under an extreme future warming scenario, none of the evaluated options suggest a reduction in lifecycle costs as the future impact occurs relatively soon requiring substantial intervention (i.e., the costs of these interventions are higher because these interventions cost substantially less in future time when a 4% discount rate is applied).

### *Lessons Learned/Considerations for Similar Assessments*

- This case study provides a theoretical example and may present varying results when evaluating a given facility.
- This case study underestimates the potential costs because it does not include the associated disruption costs realized by transportation users, such as increased time for travel delays from re-routing during repairs and maintenance.
- The choice of discount rate for the economic analysis can heavily influence estimations of present discounted costs. Lower discount rates result in higher estimates of these costs, and higher discount rates result in lower estimates of these costs. Sensitivity analysis – in this case, testing the sensitivity of results to different discounts rates – is an important practice for this type of economic analysis. Discount rate can dramatically decrease future costs associated with the impacts of climate change.
- The maintenance and rehabilitation costs are based on documentation found for CA, but the reality will vary by facility.
- Caltrans' Real Cost software platform that could potentially be adapted for estimating facility project life-cycle costs under a changing climate. In other words, this would probably mirror ADAP but could have some inherent differences in the practical application. The tool should be examined to determine if it can be run under a variety of pavement options and altered maintenance and rehabilitation schedules that represent multiple future conditions and project alternatives. The tool then would serve as a means for conducting an ADAP analysis.

### *Key Takeaways*

- This study suggests designing the road to today's conditions is most cost effective and defensible, with continued monitoring of maintenance costs and pavement condition every 5-years over the lifetime of the roadway. Given it is expected that pavement condition will deteriorate at a faster rate under a warming climate, increased maintenance and accelerated rehabilitation cycles should be expected. However, this finding could be different depending on pavement composition, acceptable levels of risk, real discount rate applied, associated new construction, maintenance and rehabilitation costs, rates of deterioration, and projected temperature conditions.
- Asphalt pavement is generally going to underperform as temperatures rise over the coming century affecting design life and pavement condition; however, due to the range of warming temperatures across the plausible futures it is unclear when this will occur (that is, within the next 20 to 50 years).
- Interventions should be evaluated to ensure reductions in potential disruptions associated with road closures and realized lifecycle costs.

## Wildfire Risk and the US Highway 50 Corridor

### *Summary*

Increased risk of wildfire can have impacts on the frequency of emergency wildfire evacuations in California and the efficacy of these evacuations to move residents out of harm's way in a timely fashion. El Dorado County officials identified the United States Highway 50 (U.S. 50) (see Figure 4)

corridor to be at-risk to wildfires. The purpose of this case study was to assess the current conditions of U.S. 50 in El Dorado County, assess the corridor's performance under future climatic conditions based on California wildfire projections, and to identify a set of suitable strategies to increase the resilience of the corridor based on cost effectiveness and other additional context-based factors. This study primarily focused on improvements to transportation asset design and operations, as opposed to evacuation and communication practices.

The U.S. 50 corridor runs east-west between South Lake Tahoe and Sacramento. It is part of the U.S. Highway System and is under Caltrans jurisdiction. In El Dorado County, U.S. 50 traverses the Sierra Foothills, running between the Tahoe National Forest and Stanislaus National Forest. It is a four-lane expressway or freeway, which transitions into a two-lane highway through the El Dorado National Forest.

Issues considered by this pilot study include: (1) existing level of service on U.S. 50 in El Dorado County and (2) current and future wildfire risk. The existing design and traffic patterns in El Dorado County are unable to accommodate current traffic levels. Congestion is prevalent at intersections to the west in Placerville. Wildfire projections show that U.S. 50 is and will continue to be highly exposed to wildfire risk into the future.

This study concluded that there are several cost-effective alternatives to improve traffic flow for evacuation (i.e., during a wildfire event), including developing an emergency flush plan, installing battery back-up technology for signals, enabling remote traffic control through Traffic Management Centers (TMCs), accurate reflection of routes on Google Maps, and updating traffic signal timing plan coordination.

Figure 4. US Highway 50, El Dorado County



### *Lessons Learned/Considerations for Similar Assessments*

- There are several cost-effective alternatives to improve traffic flows for evacuations, although the exact strategies and cost-effectiveness may differ based on context. Some of the strategies identified for this assessment were:
  - Developing an emergency flush plan
  - Installing battery back-up technology for signals
  - Enabling remote traffic control through TMCs
  - Reflecting seasonal evacuation routes accurately on Google Maps
  - Updating the traffic signal timing plan
- Consider adopting a staged strategy to implement actions that provide an immediate benefit and improvement to the area and then layer these interventions with longer-term improvements. For example, decision-makers can consider developing an emergency flush plan in the near term and plan for integrated fiber optic cable along the corridor to improve data sharing in the long term.
- Target interventions at high-risk areas. In the case of U.S. 50, the efficacy and cost-effectiveness of adaptation strategies were considered in the context of Placerville, which is where the primary traffic concerns currently exist and where evacuation-related traffic may bottleneck in the event of a wildfire.
- Leverage local/context-based expertise to identify effective strategies. In this assessment emergency response personnel in El Dorado County were consulted and helped to establish an understanding of the context and rule out certain strategies that would not be compatible with existing design.
- Additional key considerations include:
  - Feasibility: The feasibility of implementation in the geography. U.S. 50 sits within the foothills and in a national forest, making environmental clearance an arduous process, thus narrowing the alternatives.
  - Equity: Consider how vulnerable populations can benefit from the alternative(s) and implementation strategy.
  - Harmonization across jurisdictions: If multiple jurisdictions are involved in identifying and implementing the strategy, then it is important that there is communication and coordination between them. In the case of U.S. 50, Caltrans District 3 and El Dorado County share jurisdiction over the assets along the corridor.

### *Key Takeaways*

- U.S. 50 in El Dorado County is and will continue to be at high risk of wildfires into the future, emphasizing the need to improve the corridor's existing level of service and prepare for future wildfire evacuations.
- Given the geography, the assessment primarily considered adaptation strategies related to traffic and signal design and operations as opposed to considering larger projects such as roadway widening.

- It is important to leverage local traffic signal, design, and emergency response expertise when identifying appropriate context-base adaptation strategies.
- Interventions should be evaluated based on the immediacy of the need for improved traffic flows to support efficient evacuations. Simultaneously, longer term improvements should be considered to further improve the resilience of the corridor.

### Delta Sea Level Rise and Bridge Equipment Protection

#### *Summary*

Sea level rise from the Sacramento-San Joaquin Delta poses increasing flood risks to the portions of the transportation system located in the Delta. Delta sea level rise (SLR) is expected to increase water elevations, which can present both chronic flooding issues through tidal flooding or permanent inundation and acute flooding issues through storm surge. Low-lying facilities in the Delta, such as roadways, transit stops, bridges, and equipment are potentially at risk.

This case study examined flood risks associated with Delta SLR at a hypothetical transportation facility. Specifically, the case study focused on bridge mechanical and electrical equipment for a moveable bridge. Due to confidentiality constraints and available information, the case study focused on a hypothetical facility. It loosely drew on actual facility information but adjusted some of the features of the facility for demonstration purposes. The purpose of the study was to provide an example of how infrastructure managers can approach understanding to and adapting to Delta SLR.

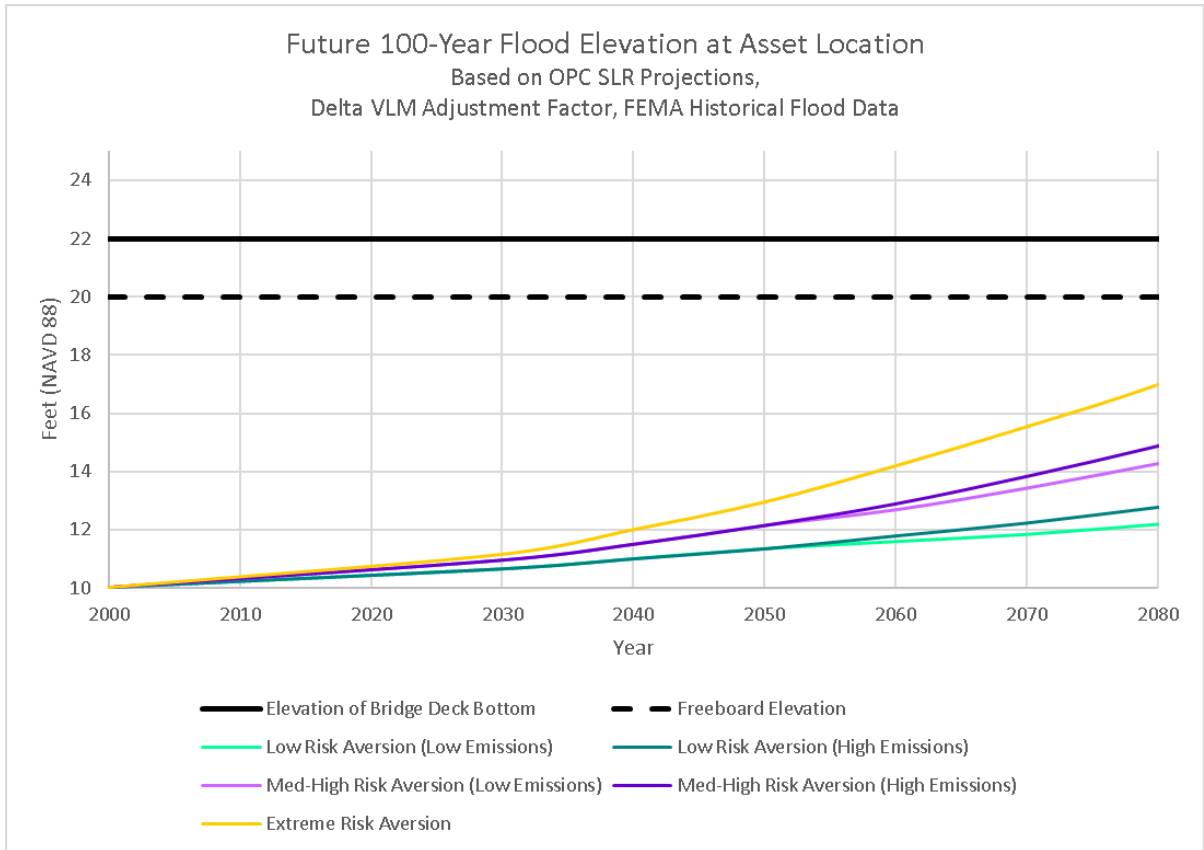
The study concluded that the existing facility performs sufficiently under different climate scenarios. However, it discusses the types of adaptation options that could be implemented and outlines how they can be evaluated.

#### *Lessons Learned/Considerations for Similar Assessments*

- Estimating flood risk in the Delta is challenging due a number of related factors such as sea level rise, tidal influences, storm surge, riverine flows, flood control and other infrastructure, and land subsidence. As subsidence continues and sea levels rise, there is increasing concern over the implications of flooding in the Delta.
- Many of the levees are aging, outdated, and sinking, and may not provide adequate protection against higher flood levels.
- Sea level rise can exacerbate flood risk due to both storm surge and chronic inundation. Project-level engineering should account for both sea level rise and changes in riverine flow due to shifting precipitation patterns.
- Several agencies and research institutions have developed estimates of sea level rise for California tide gauges where tidal data is regularly collected.
- The 2018 Ocean Protection Council (OPC) projections represent the state's official sea level rise estimates. However, the closest tide gauge to the Delta in the OPC projections is in San Francisco (Ocean Protection Council 2018). While this study used these projections for simplification purposes, further work can be done to understand sea level rise at individual locations in the Delta (see Figure 5). Several studies, including Radke, Biging et al , have analyzed the complex relationship between sea levels outside of San

Francisco Bay, in the Bay, and the Delta (John D. Radke 2017).

Figure 5. Projected 100-Year Flood Elevation at Asset Location



- Subsidence rates vary significantly across the Delta and rates of change may be much larger depending on location, which can lead to higher inundation risk from SLR and/or may damage assets if subsidence occurs unevenly.
- Consequences need to be assessed over the entire lifecycle of an asset. With climate change, these costs often increase toward the end of an asset's lifecycle as hazards intensify.
- When assessing bridge performance during flood events, it is crucial to consider scour to the abutments and, if applicable, piers. Ability to withstand impacts from debris flows also needs to be considered.
- However, because this case study focuses on the bridge's equipment, we focus primarily on elevation when evaluating its performance during flood events.
- For conceptual design, local hydraulic modeling of future conditions helps designers better understand flood risk.
- Lifecycle costing should account for not only expected future damage costs, but also for disruption costs in the event that an asset is unavailable for use. Travel volumes and detour lengths and times are helpful pieces of information for estimating these costs. Ideally, a demand model can be used to understand how the disruption of one asset affects overall network performance.

- This particular asset is an important part of both the roadway network and the navigable waterway network. Therefore, disruption consequences for both networks should be included in lifecycle costing.
- Adaptation options for equipment and sea level rise often involve either hardening in place or elevating or otherwise relocating equipment.
  - Hardening can involve sealing the exposed equipment's housing to prevent water from entering and damaging the equipment. Or, it could entail waterproofing electric cables that were not previously designed for water exposure. The specific solution depends on the type of equipment exposed and nature of the exposure. Measures to protect equipment from occasional splashing or brief submersion might not be suitable to withstand longer periods of submersion. Costs would vary greatly depending on the bridge and the specific equipment in need of hardening. Hardening in place would likely be more affordable than options such as elevating or moving the equipment. However, in many cases hardening is less likely to provide the same level of protection as moving the equipment out of harm's way.
  - Elevating or moving equipment. As with hardening, the specific solution and its cost depend on the type of equipment and nature of the exposure. In some cases, it may not be feasible to move major components of the equipment at all or without a major overhaul of all the equipment or bridge design. The primary advantage of elevating equipment would be to eliminate or significantly reduce risk, especially compared to some hardening solutions that only provide partial protection. However, in most cases it would likely be costlier to move equipment.
- Timing is also an important consideration. If flood exposure is only expected to occur late in an asset's lifecycle and adaptation options are costly to implement, then it may make sense to monitor conditions and implement the action at a later point. However, agencies should be mindful of the potentially long duration of the project planning, design, and construction process and not delay addressing issues for too long. Another option is to phase adaptation options, taking lower cost alternatives in the short term and then adjusting as needed as we learn more about the future climate, potentially implementing costlier measures farther into the future. This type of sequenced decision making is often referred to as an "adaptation pathways" approach where options are revisited at later points in time.
- Also, it is important to note that these adaptation options are framed from the perspective of an asset that already exists and is expected to undergo increased risk as the climate changes. With projects building new assets, there is an opportunity to address the climate risk in the design of the asset. The marginal costs of adapting a planned future asset to a climate-related risk are often relatively small compared to baseline alternative that assumes the climate will remain the same in the future
- As with other types of adaptation planning, cost-effectiveness should be considered alongside of analysis of how options affect disadvantaged populations and greenhouse gas emissions, per State guidance. It also involves engagement and coordination with relevant stakeholders. Some bridges in the Delta are deemed as historical per the National Register of Historic Places of the United States (National Register) and therefore require special attention. Historical bridges typically do not meet current design standards; however, replacement or rehabilitation could result in adverse effects to the historical resource. These bridges often undergo higher scrutiny, and typically the overall

aesthetic component of these bridges needs to remain after any modification is done.

### *Key Takeaways*

- Delta sea levels are projected to rise, exacerbating flood risk in the region.
- Future flood conditions should be assessed in the design of new assets. Existing assets exposed to flooding should also be assessed for increased risk.
- Lifecycle costing should be used to assess adaptation options. Costing should account for expected damage and disruption costs.

## Riverine Flooding and Bridge Retrofit/Replacement

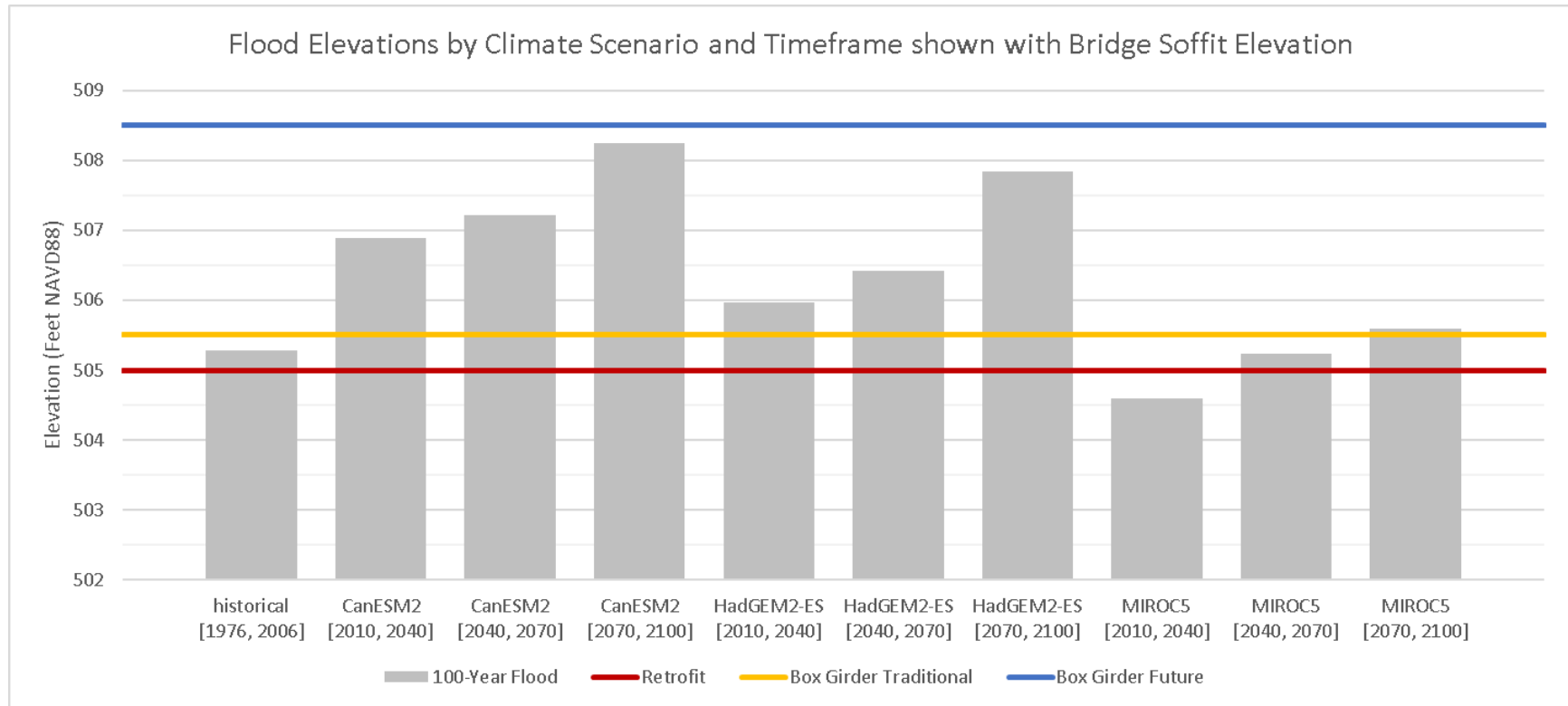
### *Summary*

Changing precipitation patterns, particularly increases in frequency and magnitude of heavy precipitation events, threaten transportation infrastructure across the SACOG region. This case study/pilot assessment examines flood risks associated with these patterns at a hypothetical bridge that needs to be refurbished or replaced on a rural roadway. Due to confidentiality constraints and available information, the case study focuses on a hypothetical facility. It loosely draws on information about an actual facility but adjusts some of the features of the facility for demonstration purposes. The purpose of the study is to provide an example of how infrastructure managers can approach understanding and adapting to changing precipitation patterns.

The hypothetical bridge is in the foothills of the Coastal Range in the western SACOG region. The creek flowing beneath the bridge is fed by rainfall and runoff from the mountains with significant seasonal variation in flows. Over the bridge, the roadway has moderate traffic volumes with an Average Annual Daily Traffic (AADT) of about 5,000. There are few parallel roadways if the facility is disrupted. The bridge already needs to be retrofitted, so there is an opportunity to build in additional capacity for future precipitation projections.

The study reviewed precipitation projections for three different GCMs and the high emissions scenario (RCP 8.5) under four future time periods: 1976–2005, 2010–2039, 2040–2069, and 2070–2099. Multiple return periods were assessed, including the 25-, 50-, 100-year storms. Both Caltrans and FEMA requirements state that bridge elevations should be built high enough to accommodate the 100-year flood. Figure 6 shows the elevations of the 100-year flood under the different modeled scenarios and the height of the hypothetical bridge deck under the different action alternatives.

Figure 6. Flood Elevations by Climate Scenario and Timeframe shown with Bridge Soffit (Deck) Elevation (RCP 8.5) (Units: feet NAVD88)



The study found that for this setting, the recommended course of action is to replace the existing bridge with a concrete box girder bridge and design it to accommodate the 100-year flood under each of the climate scenarios examined. Unlike the other representative projects, this analysis completed a full economic analysis of different adaptation alternatives see the Economic Analysis for Project-Level Planning section for more guidance on how this type of economic analysis can be conducted for other projects. Replacing the bridge with a design that can accommodate expected future increases in flows was found to be a cost-effective and risk-averse design option with overall fewer adverse social and environmental impacts than other evaluated options.

### *Lessons Learned/Considerations for Similar Assessments*

- Consider future precipitation projections in design, in addition to historical precipitation observations.
- There are several challenges with using future precipitation projections in design, including methodological differences and variation in projections between models and emissions scenarios.
- It is recommended that facility level design (1) assess projections for multiple climate scenarios; (2) use confidence intervals for projections; (3) apply state of the practice techniques for detecting and adjusting non-stationarity rather than the more traditional practice of assuming stationarity over periods over future years (e.g., 30 year periods).
- These precipitation values can be integrated as inputs into established hydrologic and hydraulic (H&H) analyses.
- Bulking factors can be applied to stream flows when debris flow from wildfire or other causes is anticipated.
- Lifecycle climate hazard costs were estimated at the facility under the different climate scenarios and adaptation options. This approach is used to measure the cost-effectiveness of the different alternatives.
- The core of the economic analysis used curves relating flood magnitudes (defined by elevations for our purposes) to their probabilities (stressor-probability functions) and flood magnitudes to their expected costs incurred (stressor-cost functions).
- For hazard costs, disruption-related costs should be included in the economic analysis in addition to damage costs. This includes the costs to users of the facility and the broader transportation system.
- Deriving the stressor-cost functions typically involves a structured conversation with one or more designers and an economist and/or cost estimator. It involves thinking about what would happen at different magnitudes of the stressor, in terms of damage costs and disruption durations. This includes magnitudes that exceed the design event. This process has not traditionally been a part of typical design practices but is an important component of resilient design.
- Applying Monte Carlo simulations<sup>6</sup> to flood events can help account for uncertainty in the

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<sup>6</sup> Monte Carlo simulations apply repeated random sampling of hazard probability distributions across each analysis year and climate scenario; by repeating this simulation hundreds or thousands of times, this method can help account for uncertainty when assessing potential future maximum hazard events.

projections and different possible patterns of extreme events over time.

- While the forward-looking bridge replacement option had slightly higher capital costs than the traditional bridge replacement, it resulted in much higher cost savings under the heavier precipitation climate scenarios and simulations. Therefore, in this case, it represented a more resilient and cost-effective design option, particularly for risk averse infrastructure managers.
- The analysis process incorporates other factors important to adaptation planning (and infrastructure planning more broadly), including social and environmental considerations and stakeholder coordination.

### *Key Takeaways*

- Future precipitation projections for multiple climate scenarios should be incorporated into H&H analysis and design.
- Assessing lifecycle costs and cost-effectiveness across multiple scenarios helps account for uncertainty in future conditions and enables identification of robust options that perform well across potential futures.
- Disruption-related costs, including costs to system users, should be incorporated into analysis.

## Economic Analysis for Project-Level Adaptation Planning

### Introduction

This section focuses on economic analysis for project-level adaptation planning. Economic analysis is a critical component of decision making for adapting to climate change, particularly given the changing and uncertain nature of the risks.

The section describes the basic parts of a methodology for lifecycle cost analysis catered to climate resiliency planning. Executive Order B-30-15 requires state and state-funded agencies to "take climate change into account in their planning and investment decisions and employ full lifecycle cost accounting to evaluate and compare infrastructure investments and alternatives (Office of Governor Edmund G. Brown Jr. 2015)."

Lifecycle cost analysis is an important step of the FHWA ADAP process (Step 8: Conduct an economic analysis). The methodology below follows the guidance of the FHWA TEACR guidance on the economic analysis portion of ADAP (Federal Highway Administration 2019). The methodology is intended to compare different project alternatives. It can be applied to different hazard and asset types. While this document focuses on lifecycle cost analysis for transportation projects, these lessons and methods can be applied to other types of economic analyses, such as economic impact analyses. This methodology can be applied both when the primary purpose of a project is to address climate risk and when a project serves another primary purpose but faces climate risk.

In addition to helping to meet state guidance, there are several benefits of using lifecycle cost analysis for climate adaptation planning:

- It develops the information needed to make cost-effective decisions in the face of climate risk.
- It generates informed discussions with internal staff and external stakeholders on financial, social, and policy implications of climate risks.
- It explores the damages and other costs associated with possible future events, rather than applying static, one-size-fits-all design criteria.
- It enables planners, designers, and financial analysts to test the sensitivity of project alternatives to changes in key assumptions and inputs. This can lead to more robust, resilient decisions.

### Approach

#### *Determine Parameters and Assumptions*

The first step of the analysis is to define key parameters and assumptions for the economic analysis. These include:

- Clearly defined set of project alternatives. These can include a baseline or existing asset, as well as different adaptation options or other alternatives.
- Discount rate used to apply to future costs and benefits to account for them being more valuable nearer in the future than they are farther into the future (e.g., receiving a dollar

tomorrow is more valuable than receiving a dollar 100 years from now). Ideally, rather than using a single discount rate, an analysis should examine how different plausible discount rates affect results.

- Start and end dates of the analysis. Determine the period over which to analyze expected benefits and costs.
- Determine monetized assumptions about disruption-related costs of hazards. These can include unit cost assumptions about value of time, vehicle operating costs, accident costs, and emissions costs. These inputs are used to help calculate socioeconomic costs caused by climate hazards under the base case and adaptation options. These costs are incurred when a hazard disrupts a facility from normal operation. The costs can include incremental time cost resulting from travelers needing to detour around the facility (and associated congestion on the network); vehicle operating costs, such as increased fuel needed for the longer routes; and incremental safety and emissions costs resulting from these longer, more congested trips. In addition to these socioeconomic costs, disruption can result in lost revenue for the agency or agencies managing the asset, if it that asset generates revenue.
- Define non-hazards costs for each alternative. These should include capital costs and can also include operations and maintenance costs. Time parameters need to be defined for these costs (i.e., start and end date or start and end year), so that they can be discounted accordingly.

### *Stressor Cost Functions*

The stressor cost function is a central component of the economic analysis. These define the expected damage costs and disruption durations for different magnitudes of stressor (e.g., flood elevations, peak flow rates, temperature, etc.). These are defined for each alternative (i.e., the base case and each adaptation option.). Figure 7 graphs the expected damage cost portion of the functions. Figure 8 graphs the expected duration length portion of the functions.

Figure 7. Example Stressor Cost Functions (Damage Component)

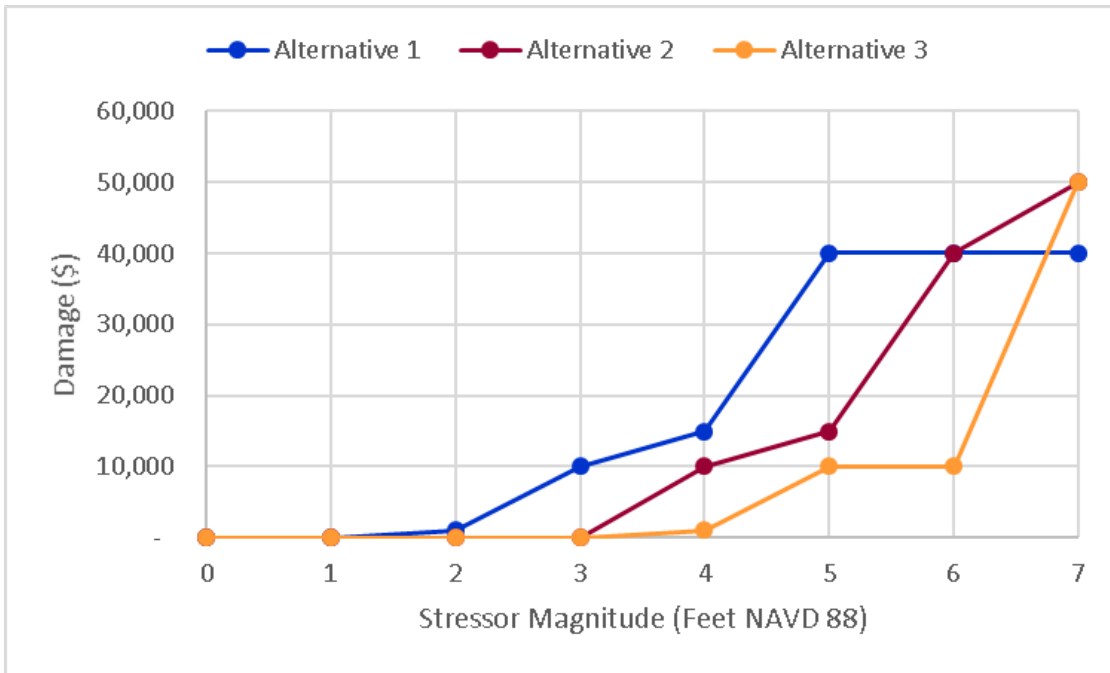
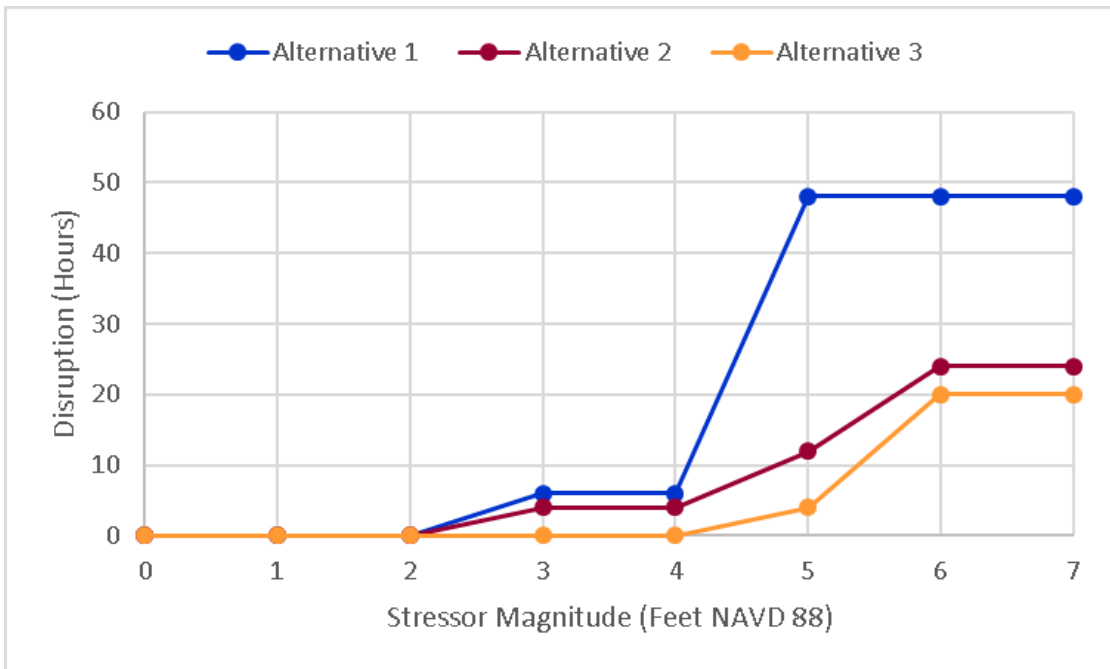


Figure 8. Example Stressor Cost Functions (Disruption Component)



Monetize Disruption

The disruption costs in the stressor cost functions need to be monetized. In other words, their units should be converted from hours (or other time units) to dollars (or other monetary units). This should be done according to the assumptions described under the "Determine Parameters and Assumptions" heading above. Generally, the monetization will follow the framework similar to the formulas listed below for time-based and mileage-based disruption costs:

$$\$/\text{Hour}_{\text{Disruption}} = \$/\text{Hour}_{\text{Disruption: Time-based}} + \$/\text{Hour}_{\text{Disruption: Distance-based}} + \$/\text{Hour}_{\text{Disruption: Lost Revenue}}$$

where:

$$\$/\text{Hour}_{\text{Disruption: Time-based}} = \Delta \text{VHT}/\text{Hour} * \$/\text{VHT}$$

where:

$$\begin{aligned} \$/\text{VHT} &= (\$/\text{hour}_{\text{Value of Time}} * (\text{Average Persons}/\text{Vehicle})) + \$/\text{hour}_{\text{Emissions cost}} + \\ &\$/\text{hour}_{\text{Safety cost}} \end{aligned}$$

and:

$$\$/\text{Hour}_{\text{Disruption: Distance-based}} = \Delta \text{VMT}/\text{Hour} * \$/\text{VMT}$$

where:

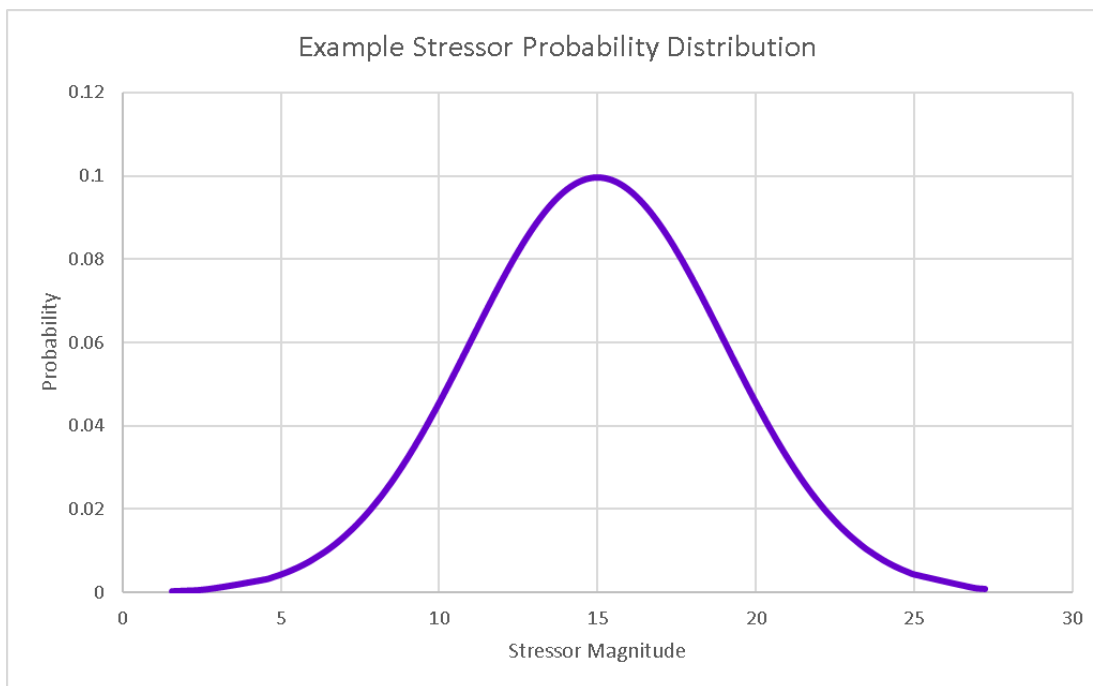
$$\$/\text{VMT} = \$/\text{mile}_{\text{Vehicle operating cost}} + \$/\text{mile}_{\text{Emissions cost}} + \$/\text{mile}_{\text{Safety cost}}$$

If more detailed information is available, then these costs can be calculated separately and then aggregated together for different dimensions of the analysis, such vehicle types, emissions types, hours of day, days of week, etc. To account for changes in expected traffic conditions over time, this monetization is often done separately for each analysis year. This is done by obtaining a set of  $\Delta \text{VHT}/\text{Hour}$  values and set of  $\Delta \text{VMT}/\text{Hour}$  values for each analysis year. Then the formulas above can be applied to monetize these disruption costs.

### *Stressor Probability Functions*

Whereas the stressor cost functions relate stressor magnitudes to costs, the stressor probability functions relate stressor magnitudes to annual probabilities. A stressor probability function is typically represented as a probability distribution for a maximum stressor magnitude in a given year. Figure 9 shows an example. Stressor probability functions are usually developed for each analysis year and each climate scenario. The format of this information can vary based on the details of a specific analysis. However, the functions are often represented by the parameters of the distribution. For example, one type of distribution often used in analyzing climate-related hazards is the Generalized Extreme Value (GEV) distribution. GEV distributions can be represented by three parameters, for location, shape, and scale. After parameters are developed for each year and climate scenario, these parameters can later be used to sample the distribution.

Figure 9. Example Stressor Probability Function



### *Simulate Hazard Events*

The next step is to simulate maximum hazard magnitudes for each year and climate scenario. This can be achieved by applying the Monte Carlo method, through a repeated random sampling of each probability distribution developed in the previous step. This simulation is performed hundreds or thousands of times. One advantage of the Monte Carlo method is that enables quantification of uncertainty in the simulations. The output of this step is a set of maximum hazard events for each analysis year, climate scenario, and simulation number.

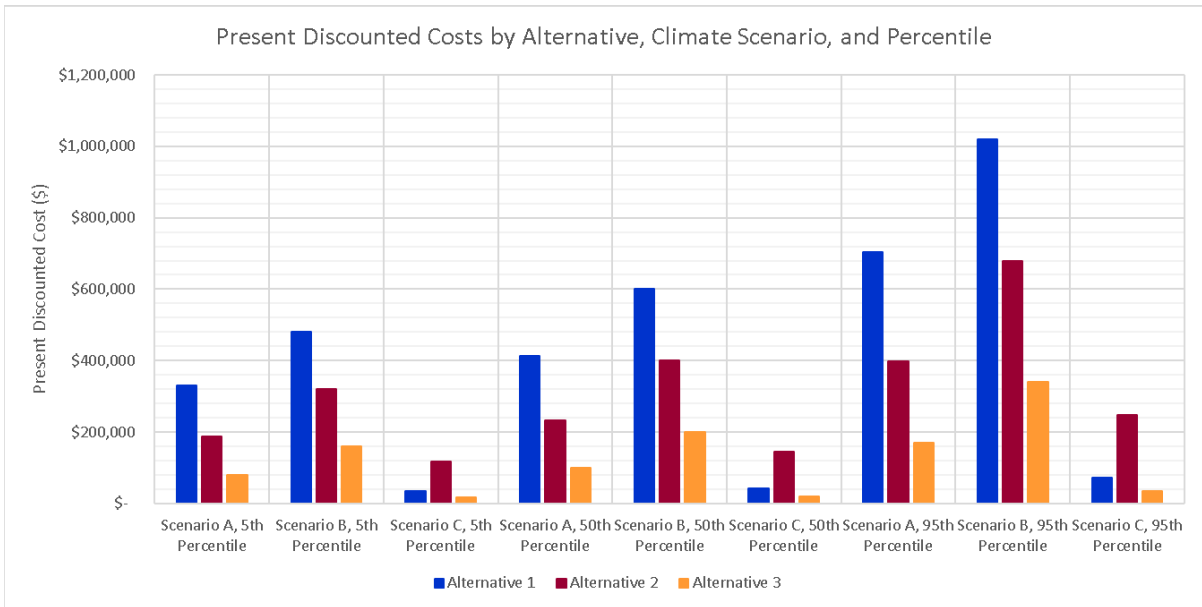
### *Calculate, Discount, and Sum Lifecycle Costs*

For each time series of maximum hazards events, the expected hazard cost can be calculated by applying the stressor cost functions. This results in a set of annual hazard costs for each analysis year, climate scenario, simulation number, and action alternative. These hazard costs can then be combined with other costs, such as capital costs and non-hazard O&M costs.

Once a time series of all costs (hazard and non-hazard) is developed for each climate scenario, simulation number, and action alternative, the discount rate can be applied. After discounting, total lifecycle costs can be tallied for each alternative, climate scenario, and simulation number.

Next, results can be aggregated across simulations. This is typically done by calculating percentiles, such as 5<sup>th</sup> percentile, 50<sup>th</sup> percentile (median), and 95<sup>th</sup> percentile. Figure 10 shows an example of present discounted costs tallied for different action alternatives, climate scenarios, and simulation percentiles. This way, decision makers can see which alternatives perform well across different climate scenarios, accounting for uncertainty within each of those climate scenarios.

Figure 10. Example Economic Analysis Results



*Performance Metrics and Sensitivity Testing*

In addition to present discounted costs, results can be shown in different formats commonly used in economic analysis. In climate adaptation planning, adaptation options are usually expected to lower hazard-related costs compared to “no action” or baseline alternatives. Thus, benefits of an adaptation option are defined as avoided hazard costs that would have been incurred under the baseline alternative.

These expected benefits can be calculated for each analysis year, adaptation option, climate scenario, and simulation number. The benefits can thus be discounted and aggregated in the same manner as described in the “Calculate, Discount, and Sum” section above. Non-hazard costs be discounted and aggregated in the same way. Finally, discounted present costs can be subtracted from discounted benefits to obtain a net present value for each alternative, climate scenario, and percentile. Discounted present benefits can be divided by discounted present costs to obtain benefit cost ratios for each alternative, climate scenario, and percentile.

Sensitivity analysis should be for important inputs such as the discount rate, damage costs, and disruption lengths. After applying lifecycle cost analysis, the process can be enhanced and reused for other assessments.

## Guidance Implementation

How the ADAP process is applied varies by the asset type and climate stressor under review. Some steps of ADAP become less applicable depending upon the specific assessment, or they may need to be approached in a different way. This section highlights the recommendations for ADAP implementation by common asset type and climate stressor combinations, based upon the findings from the representative projects outlined above.

While the guidance is provided from the perspective of using ADAP to complete a site-specific assessment, the same principles and considerations could be applied to a different assessment framework. This section provides guidance on how to walk through each type of assessment, the types of data/information that needs to be collected and considered, and any major considerations from an adaptation planning perspective for the asset/stressor combination. It is intended to be a quick reference for someone who is conducting a similar study in the SACOG region.

### Heat and Transit Stops

Understanding and assessing heat impacts at transit stops is a unique site-specific assessment. This type of study is truly an assessment of rider experience and health effects. ADAP can still be used for these types of analyses with some additional considerations and modifications. The following walks through some of the key considerations for completing a transit stop focused analysis.

Because the assessment is ultimately focused on the health of transit riders, understanding the site context (**Steps 1 and 2 of ADAP**) requires understanding the rider experience. This information can be found through:

- Population characteristics of riders (site location and local demographics),
- Stop ridership (how many people use the stop each day), and
- Heat vulnerability characteristics (e.g. proportion of people who have pre-existing conditions).

Some population characteristics can be found through tools such as CalEnviroScreen and the California Healthy Places Index. Ridership can be collected from transit agencies that service the stop. Population characteristics related to heat vulnerability specifically can be collected using the California Heat Assessment Tool.

To fully understand site conditions and user experience, conduct a survey or interview riders at the transit stop during commute times. This will be the most effective way to document existing customers including: (1) how often they use the stop, (2) how long they wait there and, (3) how comfortable they are in the heat. The survey could also ask riders about demographic information if they are comfortable providing it. Additionally, the survey could ask riders for recommendations on how to make the stop more comfortable in the heat. Survey results will provide the most accurate representation of current rider experience at the transit stop which can be used as a baseline. One other option for creating a baseline of current conditions is to measure ambient air temperature and angles of the sun throughout the year/day if resources are available.

It can be difficult to qualitatively assess how climate projections will affect the existing facility

and understand how the transit stop will perform in the future (**Step 5**). Survey information and/or physical measurements are necessary to effectively compare existing conditions against future projections. Where this information is not available, qualitatively assess how the performance of the facility may change as temperatures rise.

Comparing the performance of adaptation options may also be difficult to complete quantitatively (**Step 7**). If the information is available, then the study could identify average degrees cooling for different adaptation options and compare the compounded cooling effects of applied measures to existing and projected conditions at the transit stop. If this information is unavailable, this step could qualitatively assess appropriate cooling measures for the site.

Relatedly, it is difficult to perform an economic analysis without measured effectiveness of different adaptation measures (e.g. degrees cooling) and cost information for adaptation measures (**Step 8**). Where this information is lacking, the study can instead identify the most cost-effective and beneficial combinations of adaptation measures.

Evaluating additional considerations is very important for heat/transit stop assessments because of the emphasis on riders and public health (**Step 9**). There are many considerations that revolve around these factors which influence decision-making, including:

- Regional policies and goals
- Codes and zoning ordinances
- Disadvantaged and/or heat vulnerable populations
- Public acceptance
- Natural infrastructure
- Greenhouse gas mitigation
- Educational opportunities

These types of considerations lie outside of the technical analysis steps but can still greatly influence an adaptation decision and its implementation.

Finally, a facility management plan for a transit stop adapted to heat exposure will need to focus on maintenance requirements for adaptation measures (**Step 11**). For example, if trees are planted nearby as a heat mitigation measure, then the facility management plan should highlight maintenance needs such as periodic pruning, water needs, and other requirements such as applying fertilizer, mulch, etc.

The facility management plan can also be used to track the effectiveness of adaptation measures. In this case, develop performance indicators for the adaptation strategies at the transit stop such as:

- The stop should provide X degrees of cooling during the hottest time of day,
- The stop should accommodate space for X passengers to stand/sit in the shade at all hours of the day during summer months, and
- The stop should have X area of vegetation and tree canopy.

Then track these performance indicators against baseline conditions through periodic measurements and rider surveys.

## Heat and Rail

Heat can impact a variety of components of rail infrastructure including the rail itself, which can warp during high heat events, and the Overhead Catenary System (OCS) (light rail systems typically use an OCS), which can droop or lose connection with the train car. To assess heat impacts to rail infrastructure, narrow down the assets along the rail corridor that could be affected by temperature rise. Then, compile existing design information for those assets **(in Steps 1 through 4 of ADAP)** including:

- Zero Stress Temperature (ZST), or “rail neutral temperature,” which is the temperature where the rail is under no stress from longitudinal forces.
- The ZST is set by assessing minimum and maximum temperature ranges for the project area.
- The temperature specifications of the OCS and other electrical equipment (e.g. waystations).
- Current minimum and maximum temperature range.
- Projected, future minimum and maximum temperature range(s).

Adapting to rising temperatures **(Steps 6 and 7)** may involve re-setting the rail ZST to a higher temperature, which entails detaching or removing a section of rail and anchoring it in place again to the correct ZST.<sup>7</sup> Re-setting ZST can be done during routine rehabilitation. Adapting to rising temperatures may also involve replacing the OCS and other electrical equipment to meet higher temperature specifications. Air conditioning may need to be installed at substations or electrical equipment stations to protect sensitive systems from temperature rise. Relatively inexpensive adaptations (e.g. using routine rehabilitation to adjust ZST) may not require any economic analysis but more expensive adaptations (e.g. replacing electrical equipment) may be costly enough to warrant an economic analysis **(Step 8)**. Any implemented adaptation measures would likely benefit from a facility management plan to ensure they are working as intended under new temperature ranges **(Step 11)**.

## Heat and Pavements

Temperature influences binder grade chosen for different pavement mixes. Both minimum and maximum temperature data is used to determine pavement design. To assess heat and temperature rise impacts to pavements, the study needs to identify the following data points early on **(in Steps 1 and 2 of ADAP)**:

- Existing pavement characteristics including pavement type and which performance grade (PG) asphalt binder is used
- The function of the roadway segment in the broader network
- The dimensions of the roadway
- Any relevant pavement design criteria

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<sup>7</sup> For more information on ZST management see American Railway Engineering and Maintenance-of-Way Association (AREMA) guide: [https://www.arena.org/files/library/2013\\_Conference\\_Proceedings/Best\\_Practice\\_Guidelines\\_for\\_CWR\\_Neutral\\_Temperature\\_Management.pdf](https://www.arena.org/files/library/2013_Conference_Proceedings/Best_Practice_Guidelines_for_CWR_Neutral_Temperature_Management.pdf)

- The appropriate analysis time frame
- Estimated pavement lifespan

These data points are needed to understand the existing base case at the study site and will be used to identify necessary changes to pavement binder grade due to temperature rise. The following temperature data points need to be collected (**Step 4**) for the chosen emissions scenarios and time frames to decide if future changes in pavement design are necessary:

- Projected 7-day maximum pavement temperature(s) (°C)
- Projected 1-day minimum pavement temperature(s) (°C)

Today, Caltrans recommends a PG 64-10 binder for South Coast, Central Coast, and the Inland Valley (Caltrans CPD06-11) but based on 7-day maximum and 1-day minimum pavement temperatures processed from Cal-Adapt, the appropriate binder grade will likely shift to PG 70-10 in the 2040 – 2065 timeframe. Next, review the complete scenarios and time frames of the maximum and minimum temperatures to determine when a shift in pavement binder grade will be necessary.

Consider how existing pavement will be affected under the maximum and minimum temperature rise projections collected in Step 4. Pavement rehabilitation schedules are accelerated when the performance grade is not consistent with the surrounding temperatures, which can reduce pavement life. To combat this degradation, more maintenance, rehabilitation, and/or replacement may be necessary. Consider costs incurred over time from these activities to understand the full picture of related impacts and expenses.

The study should identify relevant adaptation options to avoid these impacts (**Steps 6 and 7**). Options may include:

- Replacing current pavements with a new pavement binder grade mix that is more appropriate for future conditions.
- Replacing current pavements with a new pavement binder grade mix during routine pavement rehabilitation or maintenance.
- Increasing proactive maintenance to decrease degradation.

Finally, the study should conduct an economic analysis of each option (**Step 8**). This involves calculating the complete lifecycle costs for adaptation options under each climate scenario. This allows for comparison of different scenarios and identification of avoided costs if adaptation is implemented. The economic analysis should provide enough information to decide a path forward.

### Wildfire and Roadside Infrastructure

Wildfire assessments of roadways can focus on infrastructure damage (e.g. burned/melted roadside infrastructure) and/or travel impacts (e.g. evacuation routing). To conduct an analysis focused on damages to roadside infrastructure, the study needs to collect the following types of information (**Steps 1 through 4 of ADAP**):

- Assets in the project area (e.g. guardrails, culverts, landscaping)
- Asset materials and design, if applicable
- Existing wildfire risk in the project area

- Projected, future wildfire risk in the project area

This information is necessary to identify the assets potentially at risk in the project area. Asset material becomes a significant factor when considering wildfire impacts. For example, a plastic culvert will be more vulnerable to damages from a wildfire than a metal one. It is also important to evaluate asset design, as some assets may be more protected than others. For example, some culverts may be designed with debris racks which will protect the culvert from clogging in the event of a wildfire.

Changing materials and designs are effective adaptation options for roadside infrastructure in wildfire risk areas (**Steps 6 and 7**). This type of assessment may not require a detailed economic analysis (**Step 8**) as it may be inexpensive/cost-effective to replace assets over time at the end of their lifecycle with a new design or asset made of different material.

### Wildfire and Bridges/Culverts

A wildfire can strip affected areas of whatever is in its path, leading to a buildup of charred vegetation, buildings, vehicles, etc. These debris can find their way into local waterways and eventually build up around bridge piers and/or clog culverts. Clogged culverts can lead to flash floods and/or standing water on the roadway. Debris around bridge piers can also block the flow of water and eventually damage the substructure.

Some adaptation strategies are focused on preventing debris build up (**Steps 6 and 7**) and should be evaluated. For example, steel mesh/cages and debris racks can be used to protect culvert entrances (see Figure 11). Protective structures, concrete rip rap, and rocks can be used to protect bridge columns and substructure from debris.

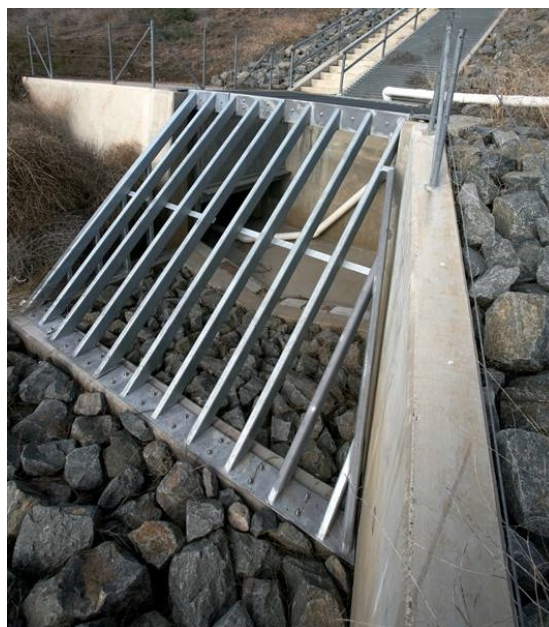
Maintenance of these adaptation measures is another key consideration as these debris cages and protective structures will need to be periodically cleaned or replaced (**Step 11**).

### Wildfire and Roadways/Travel Impacts

In the representative project example of wildfire and U.S. 50, the primary focus of the ADAP analysis was on the use of the highway as an evacuation route. To conduct an analysis of this type, the study needs to collect the following data points in **Steps 1 through 4**:

- Current and projected traffic volumes and patterns
- Crash and collision data
- Prevalence of intelligent transportation system (ITS) features
- Existing wildfire risk in the project area

*Figure 11. Rack Protecting Culvert Entrance*



[Source: Long Beach Iron Works](#)

- Projected, future wildfire risk in the project area

These data points are needed to understand current conditions which would affect an evacuation on the corridor, along with the future wildfire risk to the corridor. There are several cost-effective alternatives to improve traffic flows for evacuations, which would be identified in **Steps 6 and 7 of ADAP**. There are many different adaptation strategies including changes in operations (such as flush plans, ITS improvements, etc.), improved communications with the public and travelers, changes to asset design (such as roadway widening), and fuel load reduction (vegetation thinning practices).

For these types of assessments, it is important to target interventions in high-risk locations, i.e. where there may be an existing bottleneck along with existing/future wildfire risk. An economic analysis (**Step 8**) may be helpful to understand which strategies are most cost-effective, but it can be difficult to quantify costs of impacts to users (e.g. traffic, delays). When an economic analysis is not feasible, consider adopting inexpensive strategies that provide an immediate benefit, then layer in longer-term, more expensive strategies when resources become available.

Another key consideration for this type of assessment is the need to collect community input. Local expertise, from both the public and stakeholders, may influence decision making (**Step 9 of ADAP**). Evacuation planning should be a collaborative effort, including law enforcement and local governments, and should be made clear to the community, as they will ultimately be affected by the evacuation plan.

### Flood Impacts and Bridges

Sea level rise and/or changing precipitation patterns can exacerbate bridge flood risks. This can manifest itself in several ways, including scour or erosion at abutments and piers, debris damage to piers or bridge decks, deck overtopping, and erosion of stream banks. To assess flood impacts to bridges, it is important to collect the following information (**Steps 1, 2 and 5**):

- Bridge design, including type, and dimensions
- Storm probability the bridge is designed to withstand (e.g. historical 100-year storm)
- Any sensitive components (e.g. electrical equipment)
- Current usage (e.g. vehicular volumes, detour information, waterway volumes if it's a navigable waterway, waterway disruption cost information)

This information will be helpful for understanding current conditions and the components of the bridge that may be most vulnerable to flood impacts. To then assess future flood conditions, collect the following (**Steps 3 and 4**):

- Existing water levels and flows
- Projected changes in these flows. Information may need on one or both of the following:
  - Project precipitation changes and resulting changes in flows. Future precipitation information is available on [Cal-Adapt](#). Hydrologic analysis can be used to derive how these patterns affect flows. Cal-Adapt does have some projections of future flows for major rivers. Facility-level analysis needs to account for flood control practices such as damming and diversion.
  - Projected sea level rise (including information on how this affects storm surge). Sea level rise projections can be collected from a variety of sources, including Ocean

Protection Council and NOAA. Neither of these two sources had tide gauges with SLR projections in the Delta, so further adjustment may be needed (see further discussion in the Delta SLR/Bridge Equipment case study).

- Projected subsidence rates

Adaptation measures (**Steps 6 and 7**) may involve design changes (e.g. additional scour protection, additional freeboard) for future bridge replacements. Otherwise there may be protective adaptations that can be made such as placing rip rap or other projection around bridge columns, abutments, or nearby embankments to limit scour and erosion.

Economic analyses (**Step 8**) may be necessary to determine the level of interventions necessary in the near term and long term. The Economic Analysis for Project-Level Adaptation Planning chapter discusses important inputs for this analysis. A crucial aspect of the analysis is developing stressor cost functions for each adaptation options. In the case of bridges and flood risks, the functions the magnitude of flooding to the damage and disruption costs. Using these stressor cost functions, lifecycle cost analysis can be used to identify cost-effective adaptation options under different climate scenarios.

### Flood Impacts and Culverts

Sea level rise, storm surge, and extreme precipitation can put additional pressure on culverts that may not be sized to accommodate these larger flows if constructed based on historical flood events. To assess flood impacts to culverts, it is important to collect the following information (**Steps 1, 2 and 5**):

- Culvert design, dimensions, and material
- Storm probability the culvert is designed to withstand (e.g. historical 50-year storm)

To then assess future flood conditions, collect the following (**Steps 3 and 4**):

- Existing design storm probability flood levels
- Projected changes in the design storm and/or flood levels from sea level rise (see Flood Impacts and Bridges section above for two data sources)
- Projected subsidence rates

Adaptation measures (**Steps 6 and 7**) may involve design changes (e.g. increase capacity) for culvert replacements, installing culvert protections like steel cages and racks to prevent clogging, energy dissipation devices to slow water flow, and/or allowing for more water infiltration by expanding the area it needs to flow before/after a culvert.

Economic analyses (**Step 8**) may be necessary to determine the level of interventions necessary in the near term and long term. The Economic Analysis for Project-Level Adaptation Planning chapter discusses important inputs for this analysis. For culverts, which have shorter lifespans than bridges, it may be more viable to replace vulnerable or problem culverts in the near-term.

### Flood Impacts and Roadways

Flooding can significantly affect the traveling public if roadways collect standing water. Flash flooding can also make roadways slick and increase risk of accidents. Where possible for this type of assessment, collect design information that may affect the roadway's ability to withstand

a flood event (e.g. is the roadway on an aqueduct, is the roadway raised at all). Similarly, to the bridge and culvert assessments explained above, the study should also collect information related to future precipitation and sea level rise/storm surge projections (**Steps 1 through 5 of ADAP**). Sea level rise models can show which portions of the roadway network are in low-lying areas and/or may be exposed to future flooding. For riverine flooding, additional modeling needs to be done to understand how changes in precipitation affect flows and water levels.

Adaptation measures (**Steps 6 and 7**) may include raising the roadway to keep vehicles above water levels (e.g. on an aqueduct or by laying additional cement/pavement), installing pumps in the Right of Way (ROW) to keep flood waters off the surface of the road, installing additional culverts/increasing culvert capacity, and/or installing flood barriers to keep flood waters off the road. Depending upon the location, some natural infrastructure interventions may be possible. For example, allocating open space near roadways for natural habitat and flood water retention can mitigate flash flooding and accelerate water infiltration into the soil.

Economic analyses (**Step 8**) may be necessary to determine the level of interventions necessary in the near term and long term. The Economic Analysis for Project-Level Adaptation Planning chapter discusses important inputs for this analysis.

### Flood Impacts and Airports

Airports are often situated in wide open and often low-lying areas to facilitate ease of takeoff and landings. However, this can put them in flood prone areas. Assessing flood risk involves first collecting the following data points, among others (**Steps 1 through 4 of ADAP**):

- Identifying low-lying areas of the facility
- Especially those that may already experience flooding
- Sensitive equipment locations and design
- Current protocols during a storm event or flash flood
- Current flood protection measures
- Future extreme precipitation and/or sea level rise projections

Adapting to flood impacts is more limiting for airport facilities, as it may be disproportionately challenging to move or raise the facilities (**Steps 6 and 7**). In addition, natural infrastructure solutions such as restoring habitat or creating wetlands may not be appropriate as it attracts wildlife, specifically birds. Airports may have to rely on flood proofing and emergency response measures to protect infrastructure and keep flood waters out. These types of strategies may include:

- Water and flood barriers (e.g. flexible water barriers, flex walls, and retaining walls)
- Dry flood proofing measures (e.g. flood-proof doors, structural reinforcement)
- Emergency response (e.g. pumps)

## Recommendations for Incorporating Guidance into Activities

There are several ways for SACOG to implement the resiliency guidance into its activities, these recommendations are summarized below.

### Technical and Policy Support for Member Agencies

Much of the material in the climate adaptation Project-Level Guidance pertains to transportation projects and systems management. As SACOG does not directly manage transportation projects or systems, it can serve in a supporting role to its member counties and municipalities that do directly manage parts of the system.

Some members will likely wish to conduct climate risk assessments of transportation assets using the FHWA ADAP process presented in the Project-Level Guidance or a similar methodology. A risk assessment can help an agency formulate a strategy for making an individual asset, corridor, or subsystem more resilient to climate risks. These assessments can be used for project justification and for seeking funding from State, Federal, or other sources. As discussed in the Project-Level Guidance section, hazard resiliency is an area of emphasis at both the State and Federal levels. Risk assessments can be a standalone exercise or included as a portion of a larger project, often in the conceptual engineering or planning phase. However, members may face resource and staff constraints and encounter a few technical challenges when conducting the risk assessments.

One challenge is selecting and properly using climate projections for facility-level design. While there are many sources of readily available climate projections, they are often not suitable for facility-level decision making. This is one area where member agencies may need guidance and support. SACOG could provide specific instructions and projections (or access to projections) commonly needed for facility-level decision making (for example, precipitation Intensity Duration Frequency [IDF] curves).

Another important technical aspect of a risk assessment is the economic analysis, where the performance of different action alternatives is assessed under different future scenarios. SACOG can provide economic analysis tool and guidance to member agencies. The type of economic analysis used for estimating climate risk is distinct from traditional benefit-cost analysis given the changing probabilities of hazards over time and the need to examine multiple scenarios. Much of the legwork of building a climate risk economic analysis tool was completed for this study. See the Economic Analysis for Project-Level Adaptation Planning section for more information.

One often overlooked portion of risk assessments is the estimated consequences of disruption. Understanding how the transportation system and its users are affected by a hazard and associated disruption is necessary for effectively allocating resources and making choices about how to adapt. Agencies with a better grasp of these consequences can often make a more compelling case for improvement and investment. As the manager of the region's travel demand model, SACOG is uniquely positioned to help its members understand disruption consequences. Travel demand models can analyze how the system handles congestion when an asset is disrupted and help estimate user impacts. Although running the model can be a time-consuming process, SACOG could develop a post-processing tool that it could run for member agencies seeking to measure the system effects of a hazard on an asset. Alternatively, a simpler, "off-model" approach could be used, likely involving expected detour lengths and times and potentially information on volume and capacity.

These technical capabilities could be packaged into a suite of services that SACOG could provide members for a risk assessment or grant application. SACOG could also identify and share potential funding opportunities with members, such as the upcoming FEMA Building Resilient Infrastructure and Communities (BRIC) grant opportunity.<sup>8</sup>

In addition to these technical areas, SACOG could provide members with policy guidance to help meet State requirements and improve resiliency. These requirements include SB 379, which requires climate adaptation to be incorporated into LHMPs or safety elements of General Plans; and SB 1035, which links the housing and safety elements of General Plans in addressing climate hazards. Other relevant bills include AB 747 and SB 99, which relate to evacuation routes; and SB 1000, which requires environmental justice policies in general plans.

Another place where members can establish more resilience practices is in their design standards or manuals, or other technical documents, such as drainage manuals. SACOG can serve as a technical resource for updating these documents. These documents often include design criteria related to climate-hazards, such as the ability to withstand a 50-year flood. These standards can be adjusted to ensure that future climate projections are used in addition to historical climate observations. Care should be taken when updating these documents. The initial instinct is often to address the challenge of non-stationarity by simply updating a historical value to a future one (e.g., 'design to a 50-year storm as projected under climate scenario X'). For the reasons discussed in the Project-Level Guidance, this approach can lead to under design or overdesign of assets. Decisions are likely to be more cost-effective if, as the ADAP approach specifies, transportation managers account for uncertainty in future conditions and measure performance by looking across climate scenarios. In cases where conducting a risk analysis is infeasible or impractical, transportation managers can use design approaches such as a check event<sup>9</sup> to better understand what happens if design criteria are exceeded.

### Convening Stakeholders and Generating New Projects

SACOG can convene its members and other key regional stakeholders, such as Caltrans and transit agencies, to collaborate on improving transportation system resilience. General collaboration on climate risk and resilience in transportation system planning, design, maintenance, operations, and emergency would benefit the region, and SACOG could serve as a facilitator for an ongoing dialogue.

SACOG could also help generate ideas or concepts for new projects that address climate risks at specific locations within the region. The findings and data from the Vulnerability and Criticality Assessment will be helpful for identifying these locations.

After identifying an asset, SACOG could then convene relevant stakeholders for that asset to discuss risks and potential strategies for address those risks. This could lead to developing project alternatives and conducting a risk assessment to select a course of action. Preferred alternatives could be forwarded to the region's MTP/SCS.

For example, one of the representative projects for this study focused on a wildfire-prone section

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<sup>8</sup> <https://www.fema.gov/bric>

<sup>9</sup> A check event is one that exceeds an asset's design event.

of state-owned roadway in the Sierra. The stakeholder conversations revealed that while there is interagency collaboration on emergency response and operations, there is not necessarily a way that ideas for improving the roadway to better facilitate evacuation would be generated and materialize into projects for the MTP/SCS. SACOG could ensure that this idea generation and project conception process happens. Then, as projects materialize, SACOG could support them in some of the ways described in the previous section, such as data and tools for risk assessments and assistance with obtaining project funding.

### Existing Project Evaluation

SACOG could also integrate climate resilience into its current practices by considering climate risk when assessing project candidates for the regional flexible funding programs. There are a couple ways to do this.

One option would be to incorporate climate hazard information in SACOG's Project Performance Assessment (PPA) tool, to the extent possible. The PPA is intended to provide context about a potential project's location rather than a comprehensive evaluation of a potential project.<sup>10</sup> However, it could serve as a screening mechanism for potential climate-related risk. This could be done by either including hazard data as layers<sup>11</sup> in the PPA tool or by transferring the asset vulnerability scoring information from the *Vulnerability and Criticality Assessment* onto the transportation assets represented by the PPA. Potential projects screened for climate risk could be considered higher priority and or could be flagged for climate risks assessments.

Another way climate risk could be incorporated into the evaluation process is as a project evaluation criterion, either standalone or combined with an existing criterion. The current SACOG project performance outcomes are to:

1. Reduce regional vehicle miles travelled (VMT) per capita
2. Reduce regional congested VMT per capita
3. Increase multi-modal travel/ alternative travel/ choice of transportation options
4. Provide long-term economic benefit within the region, recognizing the importance of sustaining both urban and rural economies
5. Improve goods movement, including farm-to-market travel, in and through the region
6. Significantly improve safety and security
7. Demonstrate "state of good repair" benefits that maintain and improve the existing transportation system

A new performance outcome focused on climate adaptation and improving system resiliency could be added to this list as an eighth performance outcome. Or two other outcomes could be combined to make room for a new climate-centric one. Projects mitigating more climate risk would receive higher scores for that criterion. This could be determined by a risk assessment or

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<sup>10</sup> See "How to interpret the indicators" in the PPA tool documentation:

[https://www.sacog.org/sites/main/files/file-attachments/2020\\_project\\_performance\\_assessment\\_tool\\_documentation\\_0.pdf?1589913662](https://www.sacog.org/sites/main/files/file-attachments/2020_project_performance_assessment_tool_documentation_0.pdf?1589913662)

<sup>11</sup> While some of the climate hazard layers developed under the Vulnerability and Criticality Assessment process could be used directly in the tool, others would need to be modified or combined with the additional data to serve as an adequate screening mechanism.

other type of screening mechanism. Incorporating resiliency directly into as a project evaluation criterion could incentivize the promotion of projects that mitigate the region's risk.

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