



Risk-Based Vulnerability Assessment Findings

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TECHNICAL GLOSSARY

Adaptation Decision-Making Assessment Process (ADAP) — Process developed by the Federal Highway Administration (FHWA) for evaluating possible impacts of climate-related hazards on transportation infrastructure. The process is applied at the individual asset or project level.

Annual Maxima Series (AMS) - A series that contains the maximum daily precipitation event from each year (or another maximum daily climate event from each year).

Area-weighted mean (AWM) – Geographic statistic representing the mean value across a region. When calculating the mean, values that cover larger areas within the overall region are given more weight than values that cover smaller areas within the overall region.

Average Annual Daily Traffic (AADT) – Total traffic volume on a segment of a roadway for an entire year divided by 365 days.¹

Backcasting – The use of climate models (or other temporal models) to project values backwards into the past. This is usually done in addition to forecasting, where values are project forward into the future. Backcasting enables comparison of model results with historical observations.

Climate Adaptation – Action taken to respond to climate-relate hazards and reduce climate risk.

Climate Scenario – One projection of climate conditions over a timeframe. In this document, the term climate scenario refers to a pairing of a Global Climate Model (GCM) and a greenhouse gas emissions scenario.

Design Criteria – Specific standards that engineered infrastructure must meet. In the context of climate-related hazards, design criteria traditionally reference single storm events or conditions. For example, bridges or drainage infrastructure are often required to withstand a 100-year flood event.

Discount Rate – Rate used to discount costs and benefits that occur farther into the future compared to costs and benefits nearer in the future.

Downscaling – In climate modeling, the process of taking low-resolution outputs from GCMs and increasing their resolution for a particular region through statistical analysis of historical observations or by creating a higher-resolution regional climate model.

Flood Insurance Rate Map (FIRM) – The Federal Emergency Management Agency (FEMA) official map of a community that shows floodplains. These floodplains are developed using historical data.

Generalized Extreme Value distributions (GEVs) – A family of probability distributions used to make inferences about extreme events.²

Global Climate Models (GCM) – Simulations of the global climate over time that draw on information from physics, climatology, and historical climate observations. They use assumptions about greenhouse gas emissions and other factors to forecast future climate conditions.

Hydraulic model – Simulation of fluid behavior, often used to understand how fluid (such as streamflows) interact with infrastructure or other human-made structures. In this report, hydraulic modeling is used understand how riverine flows affect water levels and scour forces.

Hydrologic modeling – Simulation of the water system, often including process such as precipitation, runoff, infiltration, and streamflow.

Initial Abstraction - Losses of water through processes such as infiltration that occur before runoff.

¹ https://dot.ca.gov/programs/traffic-operations/census/traffic-volumes

² https://gmao.gsfc.nasa.gov/research/subseasonal/atlas/GEV-RV-html/GEV-RV-description.html





Lifecycle Cost Analysis – Economic analysis that models the expected costs over the entire period of an investment's life. This can be helpful for comparing different potential investments and understanding the tradeoff between capital spending and operations & maintenance (O&M) spending.

Link - An individual segment of roadway as represented in a travel demand forecasting model.

Link closure - A simulation run within a travel demand forecasting model to test how closing a roadway for a certain period of time would affect the overall transportation system.

Localized Constructed Analogs (LOCA) - Statistical downscaling technique that uses historical observations to improve the resolution of global climate models.³

Monte Carlo experiment – A simulation that uses repeated random sampling to generate results. This large number of results can be used to understand and quantify the uncertainty of the underlying phenomenon.

National Oceanic and Atmospheric Administration (NOAA) Atlas 14 – A compendium of precipitation data (derived from historical observations) for locations across the United States.

Precipitation Depth Frequency Curves – Curves relating precipitation depths to return periods. For example, a precipitation depth frequency curve might show the depths of precipitation for 5-, 10-, 25-, 50-, and 100-year events.

Representative Concentration Pathway - an emissions scenarios developed by the Intergovernmental Panel on Climate Change. It is a time series of emissions and concentrations of greenhouse gases in the atmosphere.

Resilience – Ability to withstand and recover from adverse events, including climate-related hazards.

Return Period - Average time between events such as precipitation events, riverine flows, floods, or earthquakes to occur.⁴ This is also known as a recurrence interval. A return period is the reciprocal of the average frequency of occurrence. For instance, a 100-year return period event has an annual probability of 1/100 (1%).

Risk – Potential for loss or expected loss. Climate risk refers to the expected loss due to climate-related hazards.

Rock Slope Protection (RSP) - Erosion prevention strategy that involves placing rock along a slope to help stabilize it

San Bernardino County Transportation Analysis Model (SBTAM) – Travel demand forecasting model for San Bernardino County.

Scour – Removal of sediment or material at the base of a structure, usually due to water.

Stressor-cost function - Curves relating flood elevations to their costs incurred.

Travel demand forecasting model (aka travel demand model or transportation system model) — Computer simulation of a transportation system that can be used to understand system behavior and the effects of certain transportation investments. They enable the user to understand how a change in on roadway (such as a closure or widening) affects travel on not only that road but also the broader system.

U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) – Commonly used hydraulic modeling software.

U.S. Army Corps of Engineers Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) – Commonly used hydrologic modeling software.

³ http://loca.ucsd.edu/

⁴ https://en.wikipedia.org/wiki/Return_period



United States Geological Survey (USGS) Streamstats – Set of tools that provide spatial information useful for water resources management and hydrologic and hydraulic modeling .

Value of Time – In the context of transportation planning, the opportunity cost of time spent traveling that could be used in other ways, such as for labor or recreation. It is often expressed as a monetary value in economic analysis.⁵

 $^{^{5}\,\}underline{\text{https://cms8.dot.gov/office-policy/transportation-policy/guidance-value-time}}$







RISK-BASED VULNERABILITY ASSESSMENT

"Our infrastructure must be resilient and sustainable to withstand these growing threats, particularly from worsening extreme events."

Paying it Forward: The Path Toward Climate-Safe Infrastructure in California

Introduction

Funded by Caltrans and spearheaded by the Western Riverside Council of Governments (WRCOG) in collaboration with the San Bernardino County Transportation Authority (SBCTA), Resilient IE is a project aimed at supporting local and regional efforts to increase transportation infrastructure resilience through development of a toolkit of resources to be used off-the-shelf or easily and cost effectively tailored to meet local needs. In addition to following the current best practices in planning for resilience, the project team sought to explore a new method for prioritizing transportation expenditures that could more adequately account for anticipated increases in the frequency and intensity of climate related hazards which test the resilience of transportation networks. This Pilot tests up and coming practices in resilience planning and offers lessons for furthering this practice to achieve a more resilient transportation network while avoiding excess expenditures.

Resilience, at its core, is acting to address the negative consequences of existing or future risks. It considers how climate-related hazards may impact infrastructure and communities. In Riverside and San Bernardino Counties, the hazards of concern are temperature and precipitation. Higher temperatures stress pavements, structures, and rail as well as threaten public health. Temperature and precipitation influence wildfires, landslides, and flooding, which present physical risks to infrastructure and safety.

Risks to transportation infrastructure are currently managed through policies established by federal or State guidance. This guidance specifies that assets be designed to a single threshold (e.g., to withstand a historical 50-year storm event). These thresholds are applied generically across assets without consideration of what happens when these thresholds are exceeded. Furthermore, traditional practice involves estimating these thresholds by analyzing past events, and therefore, are not designed for uncertain and changing conditions. With the growing interest in resilient approaches to asset design and management (captured in the quote above), new approaches are needed to ensure that design and maintenance investments are evaluated for their resiliency to forecasted climate-related changes. The importance of looking forward and thinking about future conditions is critical and should be a foundational investment process in the region.

For transportation investments, service periods extend 30 years (pavement) and 50-70 years (structures) or longer. What climate-related hazards could occur over that timeframe? And, how could infrastructure and its use by community members and businesses be impacted? These questions should be considered as a part of standard engineering practice, though they are not currently. Additionally, it is important to consider how climate-related hazards shift over time and how to make effective decisions that account for these changes.

Making Decisions

Intuitively, a process to address these concerns would follow the steps outlined in Figure 1 – conducting a robust assessment of risks and costs and using these to determine appropriate investments. Basically, the process involves understanding risk, uncertainties, consequences, and possible costs, then making a decision based on those values to ensure the asset under consideration will be built to withstand future climate-related hazards in a cost-effective manner.

FIGURE 1: Risk/Investment/Design Strategy for Infrastructure



The project assessments conducted and summarized in this document follow a framework developed by Federal Highway Administration: The Adaptation Decision-Making Assessment Process (ADAP). ADAP follows the approach shown in Figure 1 and gives transportation professionals (planners/engineers) a step-by-step guide for climate resiliency planning at the project level. The process includes the technical assessments that generate information needed by stakeholders to make robust decisions about infrastructure investments. ADAP measures cost effectiveness of different investment options to help avoid overinvestment and underinvestment. In addition to cost effectiveness, it incorporates social and environmental factors crucial to the decision-making process.

Pilot Projects

For this pilot study, two project sites were selected for analysis: Interstate (I-) 10 near Ontario Airport, and I-15 near Cajon Pass. The project team chose to include two San Bernardino County project sites to enable consistency and streamlining for this pilot effort. The sites were further selected for their regional significance and applicability for future projects in the region. Both roadways are critical to the region's transportation network and therefore both would have broader consequences if put out of service. Both locations have risks associated with flooding and changing precipitation patterns, with the I-10 location at risk from ponding due to topography and drainage capacity and I-15 at

"Designing for resilient ... conditions does not imply designing for larger discharges... Resilience implies understanding what happens when events occur that are other than the design flow."

FHWA Hydrology Design Guidance (HEC-17)

risk from erosion/overtopping from flow through a wash that runs adjacent to the roadway. The region has experienced closures along I-15 near Cajon Pass before (due to snow and wildfire) and is aware of the resulting travel impacts, which are substantial.

FIGURE 2: Project Location Map

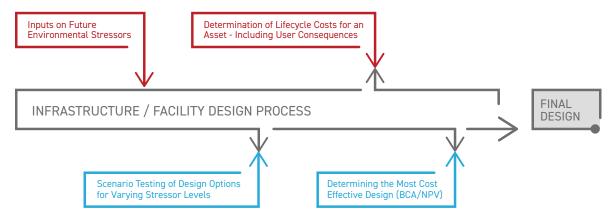


The full report presents the results of the detailed assessments completed to develop the information outlined in the steps in Figure 1. The next few pages summarize the results of that technical analysis and provide recommendations for further use. Like any technical assessment process, the results can help guide effective decisions, but are not intended to make them. Final decisions need to be based on a dialogue of potential tradeoffs. The information generated by this process provides more robust information to understand those tradeoffs.

The Process

This process utilizes a few key elements of information/data to facilitate robust design decisions. The flow diagram in Figure 3 identifies how these elements relate to the traditional design process used on virtually every major transportation project. This pilot exercise was completed to introduce the concepts of risk-based decision-making and work through a process that can be fed into traditional design to enable effective decision-making.

FIGURE 3: Risk-Based Elements of Facility Design



The technical work performed through the pilot produced key inputs needed for the normal design process. However, neither of these efforts were conducted as part of an actual facility design and neither assessed design alternatives. Doing so entails working with a design team to identify design options and costs. This information is then fed into the resilient design process to identify the most cost-effective design.

Results

The information displayed on the next two pages presents a high-level overview of the results of the technical assessments completed for the two assets.



PROJECT 1 I-10 AT NORTHHAVEN



Stressor: Precipitation

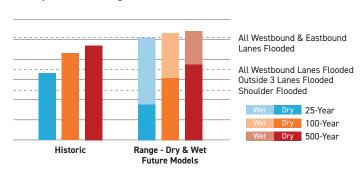
Assessment:

Flooding (Ponding on roadway) during heavy rainfall

Key Assumption:Drainage system is operating at full capacity

Precipitation Changes and Effects

Precipitation Change Predicted





System Impacts and Economic Measures

Estimated Costs to the Region from a 24 Hour Closure



Travel volumes are anticipated to increase, resulting in increased delay and cost associated with future outage events.

Lifecycle Costs



Costs from Impacts of All Predicted Future Events Discounted to Current Dollars (Range shows 25th percentile to 75th percentile results.)

Social/Environmental Measures

Increased GHG Emissions During 24 Hour Closure



Estimated Increase in Commute Time & Increase in Commute Costs



Estimated Increase in Commute Times



Travel Cost Increase - 2012-2040
Estimate Increase in Commute Costs for Low/
Moderate Income Commuters

Findings/Recommendations

- No Damage to Roadway Expected for Any Future Scenario - Precipitation May Cause Localized Flooding Only - Cause of Flooding is Limited Drainage Capacity
- System Impacts Moderate Highway Redundancy in this Area is High, Cost to Residents is Moderate
- Caltrans Should Explore Increasing Culvert
 Capacity and Monitor the Highway During
 Extreme Events
- This Project Would be Low on a List of Comparable Regional Concerns

PROJECT 2 I-15 AT CAJON JUNCTION

I-15 PROJECT

Stressor:

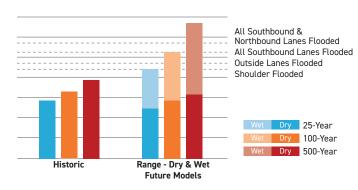
Precipitation - with Wildfire Effects on Hydrology

Assessment:

Flooding and Erosion During Heavy Rainfall

Precipitation Changes and Effects

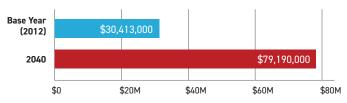
Precipitation Change Predicted





System Impacts and Economic Measures

Estimated Costs to the Region from a 24 Hour Closure



Travel volumes are anticipated to increase, resulting in increased delay and cost associated with future outage events.

Lifecycle Costs



Costs from Impacts of All Predicted Future Events Discounted to Current Dollars
(Range shows 25th percentile to 75th percentile results.)

Social/Environmental Measures

Increased GHG Emissions During 24 Hour Closure



Estimated Increase in Commute Time & Increase in Commute Costs



Estimated Increase in Commute Times



Travel Cost Increase - 2012-2040
Estimated Increase in Commute Costs for Low/
Moderate Income Commuters

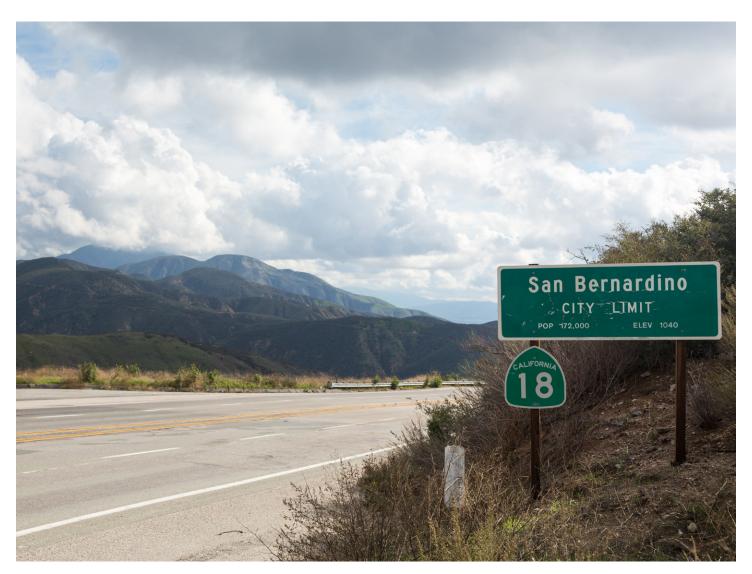
Findings/Recommendations

- Some Damage to Roadway (Erosion) May be Possible for Future Scenario - Precipitation May Cause Flooding Over the Roadway During Heavy Rain Events, Increasing After Wildfire Events
- System Impacts High Highway Redundancy in this Area is Very Low, Detours are Long and the Diversion of Traffic onto Alternate Routes Dramatically Increases Congestion
- This Project Would be High on the List of Regional Concerns

Recommendations

The results of the pilot study point to a few key findings that should be considered by transportation planners and engineers for advancing resilient approaches to asset design and management best practices. They include:

- Changing environmental conditions are anticipated to increase the intensity of precipitation events, with resulting impacts on highways. Other conditions, such as traffic volumes and land use, are also anticipated to change, increasing risk and elevating the need to consider future conditions during planning/design.
- The potential consequences of closure/damage impacts to the traveling public (residents, businesses, freight/goods movement) in the region can be substantial—particularly for roads like Cajon Pass that have limited alternative routes—and should be fully considered in decision-making.
- Data/processes are available to efficiently enable risk-based planning/design for future projects, allowing for a robust dialogue during project development and therefore long-term resilience.
- It would be beneficial for WRCOG/SBCTA or other regional agencies to provide the following as key input or tools to regional stakeholders for projects moving forward:
 - > Estimates for changing climate-related hazards and thresholds for design.
 - > Methods by which to measure system effects as an input to risk-based decisions, such as, through a streamlined traffic modeling effort.
 - > A economic analysis tool that enables planning/design teams to compare alternatives (i.e., adaptation options) and identify the cost-effectiveness of each.





1. INTRODUCTION

1.1 Objectives

The Western Riverside Council of Governments (WRCOG) and the San Bernardino County Transportation Authority (SBCTA) are working together to develop a system of evaluating climate-related hazard impacts on transportation infrastructure for the western Riverside County-San Bernardino County region (the region). The methodology will help WRCOG and SBCTA provide the basis for identifying and quantifying the impacts of climate-related hazards on transportation infrastructure, as well as evaluating climate adaptation measures and strategies that seek to maintain an acceptable level of system performance over time.

The aim of the work is to develop best practices for project-level decision making of local governments to address climate-related risks. As a result, regional partners (including local governments and Caltrans) will have access to these methods enabling operational and capital investment decisions to take potential future conditions into consideration, including the broader potential impacts of climate-related events on the traveling public. Relevant climate-related events in the region include wildfires, droughts, extreme heat, riverine flooding, and landslides.

This report documents the regional climate adaptation assessment methodology and serves as a guide for its future application. The methodology is based on the Adaptation Decision-Making Assessment Process (ADAP) developed by Federal Highway Administration (FHWA). The methodology is tested through the implementation of two transportation pilot studies in San Bernardino County.

This effort is a component of the Regional Climate Adaptation Toolkit for Transportation Infrastructure (or Resilient IE) project, initiated by WRCOG and SBCTA with grant funding from the California Transportation Authority (Caltrans) Adaptation Planning Grants program. Resilient IE is a collection of resources that provide data on climate-related hazards and tools for developing and implementing climate adaptation and resilience strategies to mitigate these risks. WRCOG and SBCTA were awarded additional funding, through a later cycle of Caltrans funding, to expand on this pilot effort with a follow-up project to be completed by February 2022.

The pilot involved applying the climate adaptation assessment methodology to two transportation assets in San Bernardino County. Each of these two pilot assessments estimated lifecycle costs associated with climate-related hazards at the location. These costs are often referred to as "do-nothing costs" or "costs of inaction". They represent the climate risk posed to an asset. In the next phase of this project, methodology will be applied to more locations and will include not only estimates of climate risk but assessments of adaptation options to address these risks at each location. The pilots served not only to estimate climate risks at two important locations in San Bernardino County, but also to test the methodology so that it can be improved for further applications.

1.2 Organization

The Executive Summary provides a brief overview for the methodology and highlights key findings of the two pilots. Chapter 2 describes context and principles for project-level climate adaptation assessments. It discusses the general methodology used for the pilots and describes how the methodology assesses impacts to the transportation system. Chapters 3 and 4 document the pilot assessment processes and results for the two pilot studies. The sections of the chapters correspond the steps of the assessment methodology. Chapters 3 and 4 are included for demonstration purposes but are not intended as direct guidance to local governments; instead, direct guidance will be provided through the next phase of work's follow-up study that will conclude in February 2022. Chapter 5 presents conclusions and reflects on lessons learned from the pilots and their implications for the next phase of the program.



2. ADAPTATION DECISION-MAKING ASSESSMENT PROCESS

2.1 Climate-Related Hazards—Impacts to the Regional Transportation System

The Inland Empire is projected to experience increased heat waves, more intense and frequent wildfires, and more extreme droughts and storms resulting in flooding and landslides. Proactively designing capital investments to be resilient with these changing conditions in mind will help protect infrastructure from being damaged during a hazard event.

The region's transportation system has become increasingly important to community viability, enabling efficient travel for personal trips, commuting, freight/goods movement to and through the region, and facilitating the rapid growth and economic strength of the area. The amount of traffic utilizing the system continues to increase, with a resulting increase in the value of the system to the community. Closures of major components of the system therefore impose shocks on the entire system, affecting area residents, businesses, and those that travel through the region for other purposes. A hazard affecting one major roadway, transit route, or other facility can be felt by users of the facility, but also by others who travel on parallel facilities. These cascading effects cause delays far from the hazard itself.

2.2 State Requirements

There are numerous state regulations and policies requiring effective consideration of climate-related hazards as an element of effective capital investment.

- Executive Order (EO) B-30-15 requires the consideration of climate-related hazards in all State investment
 decisions using full life cycle cost accounting, the prioritization of adaptation actions which also mitigate
 Greenhouse Gases (GHGs), the consideration of the state's most vulnerable populations, the prioritization of
 natural infrastructure solutions, and the use of flexible approaches where possible.
- Assembly Bill 1482 requires all State agencies and departments to prepare for climate-related hazard impacts with efforts including: continued collection of climate data, considering climate in State investments, and the promotion of reliable transportation strategies.
- Assembly Bill 2800 requires State agencies to consider potential climate impacts during planning, design, building, operations, maintenance, and investments in infrastructure. It also facilitated the formation of a Climate-Safe Infrastructure Working Group. The Working Group has since completed Paying it Forward: The Path Toward Climate-Safe Infrastructure in California, which recommends strategies for legislators, engineers, architects, scientists, consultants, and other key stakeholders to develop climate ready, resilient infrastructure for California.

How these requirements are implemented has been left largely to individual agencies, with tools and accepted processes not yet fully developed and vetted for broader application. It is contingent on regional agencies, including WRCOG and SBCTA, to identify applicable approaches to determining how to assure climate resilience as a part of capital investment.



2.3 Basis for Decisions When Considering Climate-Related Hazards

Much of current transportation decision-making practice is reliant on analysis of past conditions to establish the baseline for planning/design. Technical assessments of past weather events to determine design conditions is typical and approaches to consideration of risk are embedded in design criteria (e.g., 50-year storm) that are meant to capture broader considerations.

FHWA recognized the need for a framework for transportation project decision-making that:

- addresses uncertainties inherent in determinations of environmental conditions expected from climaterelated hazards;
- incorporates the assessment of risks to assets over an asset's service period that extended beyond just physical damage, extending to broader socio-economic considerations of the loss of transportation service;
- considers multiple adaptive design options to address physical risks noted from projected future conditions; and
- incorporates these considerations into a framework that enabled the assessment of the cost-effectiveness
 of recommended adaptation alternatives, ensuring a robust dialogue on how best to respond to noted
 long-term changes.

ADAP⁶ was developed by FHWA to address these needs and guide transportation professionals on how to evaluate possible impacts of climate-related hazards on transportation infrastructure. ADAP was developed and tested on/applied to projects that concerned various climate stressors and system effects, and was peer reviewed through multiple avenues. It has been proven to have usefulness in its application to consider long-term concerns. It is intended to be applied to an individual transportation asset (sometimes referred to as a facility).

The steps of ADAP can be summarized as follows:

- 1. researching the facility's function within its surrounding context;
- 2. identifying climate-related phenomena of concern that may have an impact on the performance of the system;
- 3. generating a set of hazard scenarios from these phenomena;
- 4. determining the impact of these hazard scenarios on the performance of the asset or system when considering climate adaption measures and no-action alternatives;
- evaluating these alternatives with respect to their impact and costs, which may include environmental and socio-economic considerations and additional factors that cannot be easily modeled (e.g., public acceptance); and
- 6. deciding on the optimal course of action and developing a management plan to maintain an acceptable level of performance throughout the lifecycle of the system.

Figure 2-1 shows the process steps.

⁶ U.S. Department of Transportation, Federal Highway Administration Office of Planning, Environment, & Realty, "<u>FHWA-HEP-17-004</u>: Adaptation Decision-Making Assessment Process (ADAP)," September 2016.





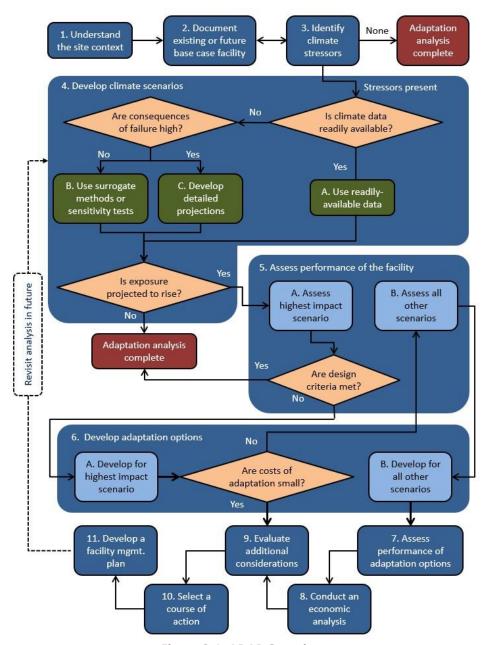


Figure 2-1. ADAP Overview

2.4 ADAP Application in the Inland Empire Region

For this initial effort, ADAP was applied to two transportation projects in San Bernardino County. This application serves as a pilot for how to tailor the implementation of ADAP to projects in the region, including projects that are already designed, but can still benefit from climate-focused analysis. The pilot studies are concerned with:

- a section of Interstate-10 near Ontario International Airport (see Figure 3-2); and
- a section of the Cajon Pass along Interstate-15 connecting San Bernardino and Victorville and locations beyond, including Las Vegas (see Figure 4-2).



For these pilot projects, the process included the quantification of the damage costs associated with the impacted individual transportation assets, the examination of how the damaged assets can disrupt the broader transportation system and affect its users (e.g., net change in travel time and net change in travel distance), and the estimation of the costs associated with this disruption. These costs can then be quantified for various design options at the asset level at any stage in the asset's lifecycle, leading to the comparison of the costs and benefits of the evaluated design options.

2.5 Assessment of Transportation System Impact

The identification of transportation system impacts is an important component of understanding climate risk. Options for analyzing system risks vary by project location nationally, but the WRCOG-SBCTA region benefits from having ready travel demand forecasting models that can be utilized to estimate traveler effects from system disruptions. These effects include additional hours of delay and miles travelled for all transportation users (rather than only those using the route that is disrupted). Travel demand forecasting models allow for an adequate analysis of these impacts⁷. Loss of access to critical transportation links will result in broader system effects as travelers of all types use varying alternate routes, increasing use on those routes and imposing additional system delays. To understand the full impact, the totality of system changes (e.g., increases in mileage traveled and delay) should be calculated and understood as a key factor of decision-making.

For this work, the San Bernardino County Transportation Analysis Model (SBTAM) was applied, with support provided by SBCTA and its consulting team. The basic analysis methodology included conducting before and after studies of link closures⁸—noting travel expectations of the regional network for a normal day and one where the link being analyzed (done separately for I-10 and I-15) was closed to any traffic. The resulting system impacts, measured in miles detoured and delay time, were analyzed to quantify the broader system impacts of such closures and identify metrics that could be converted into user costs as an input element to the benefit-cost assessment conducted for both projects. Using guidance provided by FHWA increases in traveler miles travelled and hours travelled were monetized (i.e., converted to dollar values for the purposes of analysis).

Using this type of modeling framework for these types of assessments is particularly helpful in California, where State legislation requires the consideration of impacts on the environment and low-moderate income wage earners as a measure of guiding appropriate investments. Model outputs can be analyzed to assess impacts on various system users (i.e., freight) or by socio-economic metrics contained in the model (i.e., household auto ownership and income levels). Outputs can also be used to identify increases, resulting from system delays and increased miles travels, in criteria pollutants (i.e., carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide), which are important to meeting air quality standards, and GHGs, which are critical to statewide and regional climate mitigation efforts. These measures were not analyzed comprehensively in the pilots, but they are noted as potential outcomes of later analyses using ADAP.

The metrics that resulted from the analysis of system effects are presented in the following sections and are utilized in the quantification of lifecycle cost estimates associated with changing baseline conditions.

⁷ Traditional assessments that are only focused on evaluating the effects of disruption on the detour routes that impacted travelers may utilize produce limited results that are not representative of the broader impacts that could be observed during these disruptions.

⁸ "Links" refer to individual segments of roadway as represented in the travel demand model. A link closure refers to a simulation run within the model to test how closing a roadway for a certain period of time (e.g., 24 hours) would affect the overall transportation system.





3. PILOT 1: INTERSTATE-10 NEAR ONTARIO AIRPORT

3.1 Step 1: Understand the Site Context

The Interstate-10 (I-10) section pilot study focused on a segment of highway near the Ontario International Airport, which will be undergoing a highway widening project consisting of shoulder widening and construction of a retaining wall. The improvement is part of a larger, 33-mile project that proposes to add freeway lanes along the corridor to reduce traffic congestion, increase throughput, and enhance trip reliability. **Figure 3-1** shows the project vicinity map.

The segment analyzed is on the I-10 between North Haven Avenue and Milliken Avenue. The site is in Caltrans District 8. **Figure 3-2** shows the segment used in the pilot study. **Figure 3-3** shows an aerial photo of the segment. The 2016 Caltrans estimated Average Annual Daily Traffic (AADT) count for this segment of I-10 was 266,000⁹

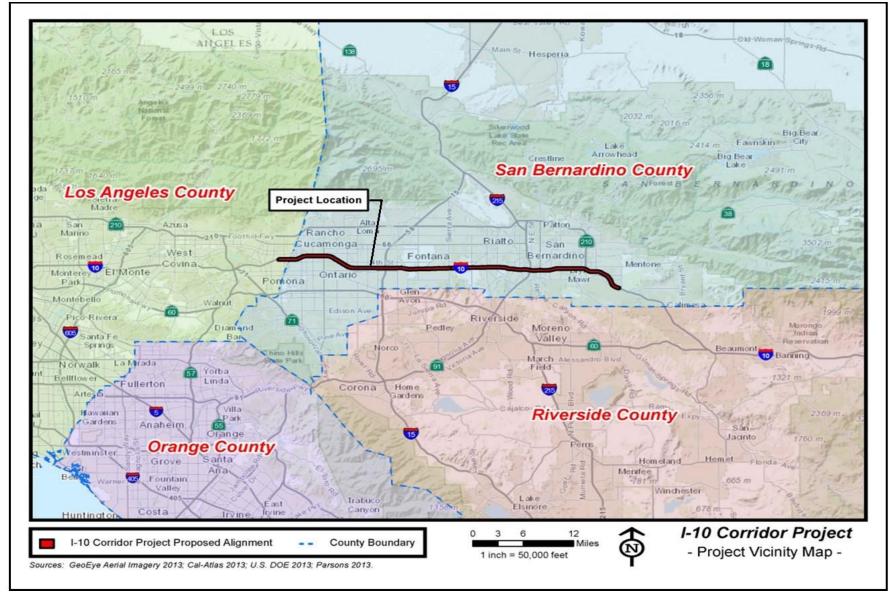
Portions of the westbound shoulder and outer lane are located within a Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) Flood Zone AH—defined by FEMA as "areas subject to inundation by 1-percent-annual-chance shallow flooding (usually areas of ponding) where average depths are between one and three feet"¹⁰. **Figure 3-4** shows the FEMA FIRM, and **Figure 3-5** shows the United States Geological Survey (USGS) StreamStats watershed for this location. Freeway travel interruption at this location has a potential to impact access to and from the airport in addition to other local and regional destinations.

⁹ https://dot.ca.gov/-/media/dot-media/programs/traffic-operations/documents/census/aadt/tc-2016-aadt-volumes-a11y.pdf

¹⁰ https://www.fema.gov/media-library-data/1538670901229-81423feb161c06426ac157a409123f3d/app-h flood maps 508 oct2018.pdf







Source: Interstate 10 Corridor Project, Final Environmental Impact Report/Environmental Impact Statement, 2017

Figure 3-1. Project Vicinity Map







Figure 3-2. Project Location Map



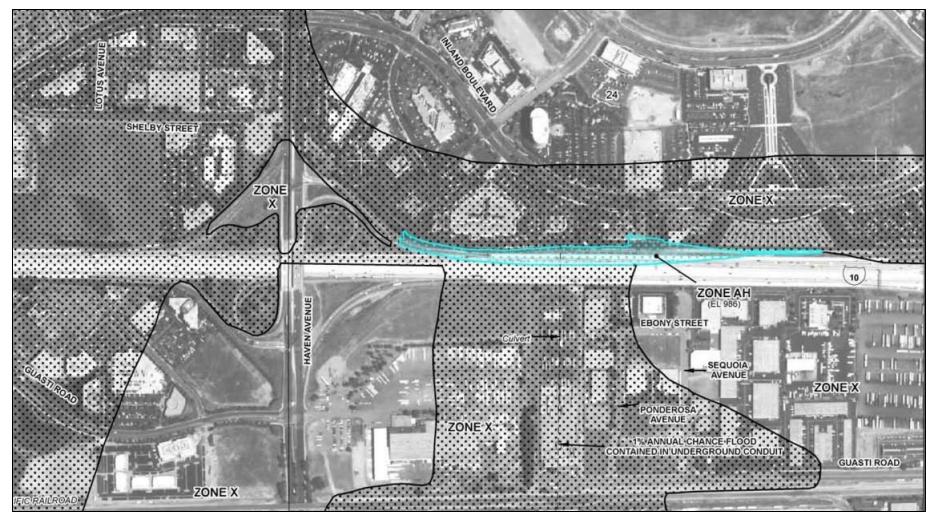


Imagery © 2019 Google, Data USGS, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Data LDEO-Columbia, NSF, NOAA, Landsat / Copemicus, Data CSUMB SFML, CA OPC, Data MBARI, Map data © 2019 50 ft ii

Figure 3-3. Project Location Aerial - Westbound View.







Source: Interstate 10 Corridor Project, Final Environmental Impact Report/Environmental Impact Statement, Floodplain Evaluation Report, 2014

Figure 3-4. FEMA FIRM



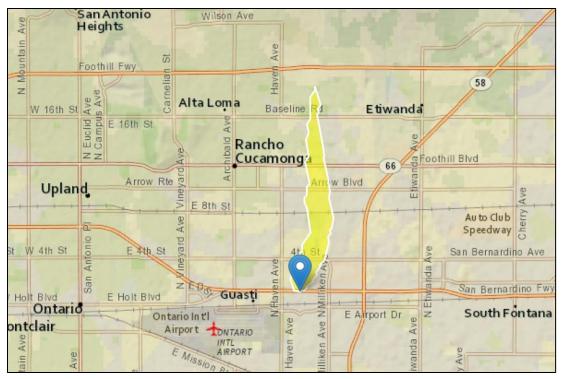


Figure 3-5. I-10 USGS StreamStats Watershed

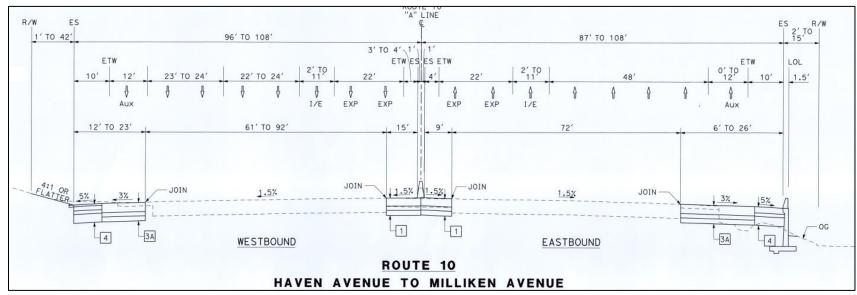
3.2 Step 2: Document Existing or Future Base Case Facility

The I-10 segment between North Haven Avenue and Milliken Avenue modified by the widening project is the 'base case facility' for the pilot assessment. The proposed widening, named the I-10 Corridor Project (CP), through this location extends from approximately 0.4 miles west of White Avenue in Pomona to Live Oak Canyon Road in Yucaipa¹¹. **Figure 3-6** shows a typical cross section of the proposed project on the analysis segment.

¹¹ Interstate 10 Corridor Project, Final Environmental Impact Report/Environmental Impact Statement, 2017







Source: Interstate 10 Corridor Project, Final Environmental Impact Report/Environmental Impact Statement, Geometric Approval Drawings, Alternative 3, 2017

Figure 3-6. Analysis Segment – Typical Cross Section



The current I-10 mainline consists of four general purpose (GP) lanes and one high-occupancy vehicle (HOV) lane in each direction, with auxiliary lanes (i.e., ramp-to-ramp lanes between an on-ramp and the next off-ramp) on some segments between the Los Angeles-San Bernardino County line and Haven Avenue interchange. Between the Haven Avenue and California Street interchanges, the freeway mainline consists of four GP lanes in each direction, with auxiliary lanes on some segments. Between Haven Avenue and Milliken Avenue, the I-10 CP Alternative 3 proposes widening with the following westbound and eastbound lane configurations: shoulder, auxiliary lane, 4 regular lanes, one ingress/egress (I/E) lane for the express lanes, and 2 express lanes.

Upon review of the Floodplain Evaluation Report for the I-10 CP, a location near Haven Avenue was identified as being in the 100-year flooding on the westbound shoulder and outer lane. As described above, the area is designated by FEMA as Flood Zone AH. There is a concrete-lined trapezoidal channel that runs parallel to the I-10 alongside the westbound lanes. The channel feeds into a culvert that cuts under the freeway in a perpendicular manner. **Figure 3-7** shows the channel and culvert entrance.

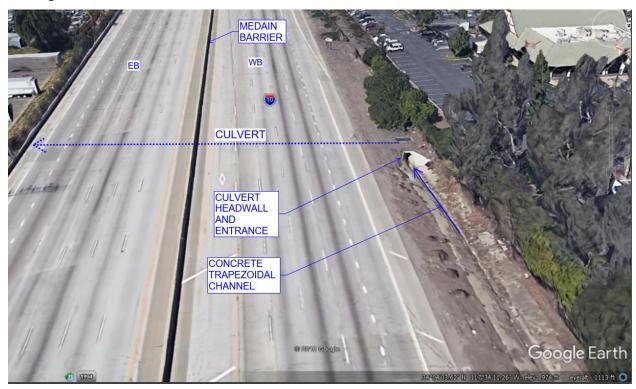


Figure 3-7. I-10 Roadside Channel and Cross Culvert

The existing culvert capacity can restrict flow and cause ponding at this location. In very heavy flow events, this ponding water can spill onto the freeway. The median barrier serves as a maximum flooding limit for the westbound lanes, preventing water from spilling onto the eastbound lanes. In extreme flood scenarios that exceed that the barrier height, the water would spill over to the eastbound lanes.

3.3 Step 3: Identify Climate Stressors

Precipitation is the primary environmental factor that affects the roadway. This effect is anticipated to change because of future climate-related conditions. Increased precipitation can lead to more frequent and intense flooding.





3.4 Step 4: Develop Climate Scenarios

Developing climate projections was not part of the scope of the pilots. Therefore, previously developed gridded¹² precipitation projections were used.

Data Source

These projections are from Global Climate Models (GCM) that had been downscaled by the Scripps Institute of Oceanography with a technique called Localized Constructed Analogs (LOCA)^{13,14}. Ten GCMs were identified by California State agencies as being representative of climate conditions across the state¹⁵. Three of these ten were used for the assessment.¹⁶

The future impacts climate-related hazards are uncertain as they will be affected by current and future greenhouse gas emissions. Each climate model is run for two greenhouse gas emission scenarios, Representative Concentration Pathway (RCP) 4.5 and 8.5. RCP 4.5 assumes that global emissions decrease starting in 2050, where as RCP 8.5¹⁷ assumes that emissions will rise through 2100¹⁸. This pilot uses RCP 8.5 to provide a conservative estimate and the worst potential hazard impacts.

Data Processing

These projections had been previously processed further using the following steps:

- Annual Maxima Series (AMS)¹⁹ were derived for each climate scenario.
- Generalized Extreme Value distributions (GEVs) were fit to four 30-year time slices of the AMS for each climate scenario: 1976-2005, 2010-2039, 2040-2069, and 2070-2099.
- These distributions were used to estimate precipitation values corresponding to the 2-, 5-, 10-, and 25-year events.
- Percentage changes between backcasted values (i.e., 1976-2005) and forecasted values were calculated.
- For each climate scenario, percentage changes were applied to the National Oceanic and Atmospheric Administration (NOAA) Atlas 14²⁰ precipitation values for the applicable return periods. NOAA Atlas 14 estimates are based on observed historical data.
- Given the relatively small sample of 30 years for each modeled time slice, percentage changes for 25-year events were applied to 50-, 100-, 200-, and 500-year events from NOAA Atlas 14.
- Drainage basins upstream of the analysis location were delineated using the USGS StreamStats²¹ tool. **Figure 3-5** depicts the watershed.

¹² Gridded means that the projections are given in a grid of rectangles corresponding with different geographic coordinates. Each rectangle has its own projection.

¹³ http://loca.ucsd.edu/

¹⁴ Projections were originally downloaded from the Cal-Adapt Data Server: http://albers.cnr.berkeley.edu/data/scripps/loca/

¹⁵ http://www.water.ca.gov/climatechange/ docs/2015/Perspectives Guidance Climate Change Analysis.pdf.

¹⁶ The models used are: CanESM2, HadGEM2-ES, and MIROC5.

¹⁷ The term Representative Concentration Pathway (RPC) refers to one of the emissions scenarios developed by the Intergovernmental Panel on Climate Change. It is a time series of emissions and concentrations of greenhouse gases in the atmosphere. For more information, see: https://www.ipcc-data.org/guidelines/pages/glossary/glossary/r.html.

¹⁸ https://cal-adapt.org/tools/

¹⁹ Annual Maxima Series refers to a series that contains the maximum daily precipitation event from each year.

²⁰ NOAA Atlas 14 contains precipitation data (derived from historical observations) for locations across the United States: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds map cont.html

²¹ https://streamstats.usgs.gov/ss/



 Finally, area-weighted mean (AWM) precipitation estimates were developed for the drainage basin using the gridded projections.

Recommended Improvements

The following recommended improvements to this methodology should be included in future risk assessments. The pilot projects had a limited scope and therefore, these practices were not included.

- More than one emissions scenario should be used.
- A larger set of GCMs should be used.
- Rather than assuming stationarity for each 30-year period, the GEVs should be fit with a time parameter to account for non-stationarity.
- Projections should be tested for bias, and biases should be corrected as needed.
- Confidence intervals should be developed for each set of projections and for NOAA Atlas 14 estimates.
- Percentage changes from 25-year events should not be assumed to apply to other events.

Resulting Climate Projections

Figure 3-8 shows the watershed precipitation depth frequency curves for a 24-hour duration event. **Figure 3-9** shows the temporal change in the 10-year/24-hour precipitation depth for each climate scenario alongside the historical depth from NOAA Atlas 14.

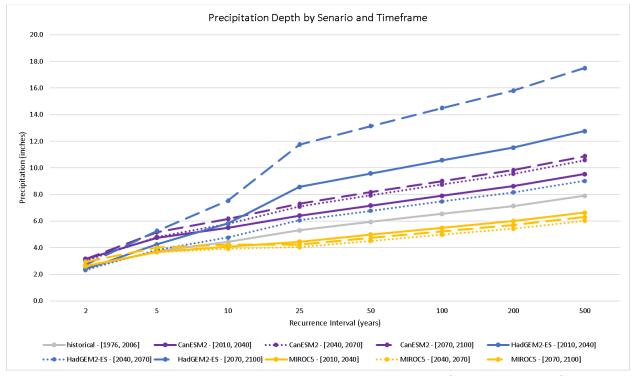


Figure 3-8. I-10 Drainage Basin - Precipitation Depth Frequency Curves (24-Hour Duration), RCP 8.5





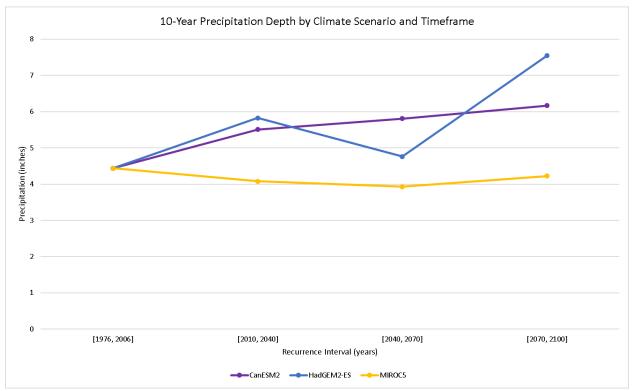


Figure 3-9. I-10 Drainage Basin - Precipitation Depth 10-Year Event (24-Hour Duration), RCP 8.5

There is substantial variation between the projections, including between the models and between the timeframes within each model. For example, the HadGEM2-ES 2070-2099 projections are higher than other projections. This variation can be partially attributed to the substantial uncertainty regarding future extreme precipitation events and to the methodology used. The integration of the recommendations previously listed is therefore important to reduce part of the observed variation. However, using the estimated projections is still helpful as a stress test of climate conditions to the facility.

3.5 Steps 5: Assess Performance of the Facility

Assessing the performance of the facility requires hydrologic and hydraulic assessments. A hydrologic assessment can be used to estimate peak flows given the precipitation projections. In turn, a hydraulic assessment can be used to estimate flood elevations given the peak flow projections.

3.5.1 HYDROLOGY

The USGS StreamStats program was utilized to delineate the watershed at the culvert entrance location. The USGS StreamStats watershed delineation and basin characteristics were used to estimate 25-, 50-, 100-, 200-, and 500-year return period peak flows at the culvert based on historical data.

While using a hydrologic model of the watershed near the facility to forecast future peak flows is recommended, due to the limited scope of the pilot studies, hydrologic modeling was not conducted.²² Instead, future peak flows were estimated by scaling the historical peak flows based on the relationship between historical precipitation and future precipitation.

²² This hydrologic modeling should incorporate both projected changes in precipitation patterns and changes in upstream urbanization that could affect flows.



3.5.2 HYDRAULICS

To determine flood elevations for each of the historic and future peak flows at the culvert, the U.S. Army Corps of Engineers Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) was utilized to calculate peak flood flows and the resulting flood elevations at the culvert entrance. This analysis required the development of flood hydrographs to route through the culvert accounting for storage within the channel, roadway, and adjacent parking lot. The calculation procedure utilized the following steps:

- 1. Calculate calibrated peak flows at the culvert entrance matching the historical and future peak flows estimated previously. HEC-HMS basin parameters are:
 - Basin Area: 1.7 square miles
 - Loss Method: SCS Curve Number (composite Curve Number of 62)
 - Transform Method: SCS Unit Hydrograph (SCS Type I)
 - 24-hour precipitation: data obtained from NOAA Atlas 14
 - NRCS Lag Time: 60 minutes
 - Initial Abstraction²³: 1.16 to 2.0 inches
- 2. Develop Elevation, Storage, and Discharge functions for culvert and input to HEC-HMS
 - Elevation versus Storage relationship was determined by measuring the area at each of the contour levels from elevation 976 (culvert entrance) to elevation 990 using the topography on the Geometric Approval Drawings. Incremental storage and total storage were then calculated at each elevation level.
 - Elevation versus Discharge relationship for culvert was determined using Bentley CulvertMaster software based on the estimated culvert dimensions.
 - Elevation versus Discharge relationship for flow over median barrier was determined assuming weir flow over barrier using Bentley Flowmaster software.
- 3. Run HEC-HMS with elevation-storage-discharge relationships to determine resultant flood elevations for each of the peak flows.

Table 3-1 provides a summary of the calculated peak flows and corresponding flood elevations at the culvert. Note that overtopping of the median barrier begins at about elevation 988. **Figure 3-10** graphs the **Table 3-1** elevation results for each scenario and return frequency.

Table 3-1. Hydrology and Hydraulic Analysis Results

			Return Frequency 25 50 100 200 500						
		25							
Historical									
[1976, 2006]	Peak Flow Stream Stats (cfs)	318	405	494	594	711			
	HEC-HMS Peak Inflow (cfs)	318	405	493	594	711			
	HEC-HMS Peak Outflow (cfs)	259	280	296	312	326			
	HEC-HMS Flood Elevation (feet)	984.7	985.6	986.3	987.0	987.7			

rcp85

CanESM2

²³ Initial Abstraction refers to losses of water before runoff through processes such as infiltration.





			Ret	urn Freque	ency	
		25	50	100	200	500
[2010, 2040]	Peak Flow Stream Stats (cfs)	473	598	711	830	994
	HEC-HMS Peak Inflow (cfs)	473	598	326	830	994
	HEC-HMS Peak Outflow (cfs)	293	312	326	484	774
	HEC-HMS Flood Elevation (feet)	986.2	987.0	987.7	988.1	988.2
[2040, 2070]	Peak Flow Stream Stats (cfs)	586	717	853	996	1193
	HEC-HMS Peak Inflow (cfs)	586	717	853	996	1193
	HEC-HMS Peak Outflow (cfs)	311	327	527	776	1075
	HEC-HMS Flood Elevation (feet)	987.0	987.8	988.1	988.2	988.2
[2070, 2100]	Peak Flow Stream Stats (cfs)	618	755	898	1048	1256
	HEC-HMS Peak Inflow (cfs)	618	755	898	1048	1256
	HEC-HMS Peak Outflow (cfs)	315	332	613	858	1169
	HEC-HMS Flood Elevation (feet)	987.2	988.0	988.1	988.2	988.2
HadGEM2-ES						
[2010, 2040]	Peak Flow Stream Stats (cfs)	821	1003	1193	1393	1668
	HEC-HMS Peak Inflow (cfs)	821	1003	1193	1392	1668
	HEC-HMS Peak Outflow (cfs)	466	782	1075	1337	1646
	HEC-HMS Flood Elevation (feet)	988.1	988.2	988.2	988.2	988.3
[2040, 2070]	Peak Flow Stream Stats (cfs)	422	533	644	752	901
	HEC-HMS Peak Inflow (cfs)	423	532	644	752	901
	HEC-HMS Peak Outflow (cfs)	284	302	318	332	617
	HEC-HMS Flood Elevation (feet)	985.7	986.6	987.3	988.0	988.1
[2070, 2100]	Peak Flow Stream Stats (cfs)	1440	1758	2091	2441	2924
	HEC-HMS Peak Inflow (cfs)	1440	1758	2091	2442	2924
	HEC-HMS Peak Outflow (cfs)	4397	1746	2081	2435	2917
	HEC-HMS Flood Elevation (feet)	988.3	988.3	988.4	988.4	988.5
MIROC5						
[2010, 2040]	Peak Flow Stream Stats (cfs)	213	276	343	413	509
	HEC-HMS Peak Inflow (cfs)	213	276	343	414	510
	HEC-HMS Peak Outflow (cfs)	207	243	267	282	299
	HEC-HMS Flood Elevation (feet)	982.9	984.1	985.1	985.7	986.4
[2040, 2070]	Peak Flow Stream Stats (cfs)	162	220	275	334	415
	HEC-HMS Peak Inflow (cfs)	161	220	274	334	416
	HEC-HMS Peak Outflow (cfs)	160	212	243	266	282
	HEC-HMS Flood Elevation (feet)	981.7	983.1	984.1	985.0	985.7
[2070, 2100]	Peak Flow Stream Stats (cfs)	186	246	307	371	459
	HEC-HMS Peak Inflow (cfs)	185	246	307	372	459



	Return Frequency				
	25	50	100	200	500
HEC-HMS Peak Outflow (cfs)	182	228	255	273	291
HEC-HMS Flood Elevation (feet)	982.2	983.6	984.6	985.3	986.1

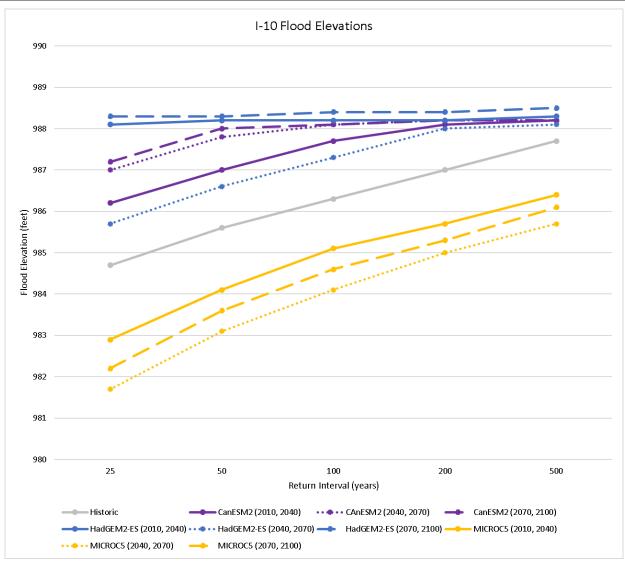


Figure 3-10. Elevation Results Graph

3.6 Step 6: Develop Adaptation Options

This step involves developing strategies to address the climate-related risk posed to the asset. These can include design, operational, maintenance, policy, or other measures often referred to as adaptation options. While developing adaptation options was not part of the pilot assessment scope, the next phase of this project will develop and assess adaptation options for different locations.





3.7 Step 7: Assess Performance of Adaptation Options

This step involves assessing the performance of the adaptation options developed in Step 6. It applies an analysis like the one conducted in Step 5 to each adaptation option to understand how the option addresses the climate risk in comparison with the baseline 'no action' option. While assessing adaptation options was not part of the pilot assessment scope, the next phase of this project will assess the performance of adaptation options for different locations.

3.8 Step 8: Conduct an Economic Analysis

For the economic analysis, lifecycle climate hazard costs were estimated at the facility under the different climate scenarios. The lifecycle cost analysis is documented in a spreadsheet that accompanies the deliverable. Because adaptation options were not developed as part of the pilot assessment, only the base case facility was analyzed. When multiple adaptation options are analyzed, capital and operations and maintenance costs should be included along with costs related to the probable occurrence of climate hazard events. With this additional information, the economic analysis can be used to measure the cost effectiveness of the different action alternatives.

The spreadsheet was used to calculate expected cumulative costs to the asset over time. To do this, it uses curves relating flood elevations to their probabilities (from Step 5) and flood elevations to their costs incurred (stressor-cost function). Every time a facility is flooded, costs are calculated per the stressor-cost function and summed for all such events over time. Due to the limited scope of the pilot assessment, it was assumed that the asset is not improved when damage does occur. This assumption is unlikely to hold when damage costs are high and there are feasible options for mitigating the impacts. **Table 3-2** shows some of the basic inputs to the lifecycle cost analysis. The spreadsheet documents these inputs, as well as other assumptions, in greater detail.

InputValueReal Discount Rate3%Analysis Start1/1/2020Analysis End1/1/2100Value of Time (VOT)27.20 2015\$/hourLight Duty Vehicle Operating Costs (VOC)0.39 2017\$/mileCommercial Truck VOC0.90 2017\$/mile

Table 3-2. Lifecycle Cost Analysis Basic Inputs

Costs accounted for in the analysis include physical damage repair costs, incremental travel time costs, and incremental travel distance costs. **Table 3-3** shows the stressor-cost function for the location.²⁴ It provides physical damage in 2019\$ terms and disruption durations in days.

²⁴ Buildings impacts are excluded from the lifecycle cost assessment.



Table 3-3. I-10 Stressor Cost Function

Flood Elevation (feet)	Flow Magnitude (cfs)	Physical Damage Repair & Maintenance Cost		Travel Lane Flooding	Haven Ave. Westbound Offramp	Haven Ave. Westbound Loop Onramp	Haven Ave. Westbound Onramp	Milliken Westbound Onramp	Total Lanes	Flood Lanes Affected
	-	-	-						14	0
976	-	-	-	Contained	No flooding	No flooding	No flooding	No flooding	14	0
977	-	-	-	Contained	No flooding	No flooding	No flooding	No flooding	14	0
978	-	-	-	Contained	No flooding	No flooding	No flooding	No flooding	14	0
979	-	-	-	Contained	No flooding	No flooding	No flooding	No flooding	14	0
980	-	-	-	Contained	No flooding	No flooding	No flooding	No flooding	14	0
981	-	-	-	Contained	No flooding	No flooding	No flooding	No flooding	14	0
982	161	-	-	Contained	No flooding	No flooding	No flooding	No flooding	14	0
983	213	5,500	0.25	Partial shoulder flooding	No flooding	No flooding	No flooding	No flooding	14	0
984	246	8,800	0.25	Shoulder + Outer 3 WB lanes flooded (0-1 foot)	No flooding	No flooding	No flooding	Closed due to WB lane flooding	14	3
985	334	8,800	0.50	All WB lanes flooded (0.5 to 2 feet)	Flooded	No flooding	No flooding	Closed due to WB lane flooding	14	7
986	423	11,000	0.50	All WB lanes flooded (1.5 to 3 feet)	Flooded	No flooding	No flooding	Closed due to WB lane flooding	14	7
987	598	11,000	0.50	All WB lanes flooded (2.5 to 4 feet)	Flooded	Flooded	No flooding	Closed due to WB lane flooding	14	7
988	755	11,000	0.75	All WB lanes flooded - Top of median barrier	Flooded	Flooded	Partial Flooding	Closed due to WB lane flooding	14	7
989	2,924	15,500	1.00	All WB/EB lane flooded - overtopping median barrier	Flooded	Flooded	Flooded	Closed due to WB lane flooding	14	14





For the physical damage repair and maintenance, the following assumptions were used:

- Maintenance costs along roadway assumed to be initiated when channel becomes full and begins to spill onto roadway (elevation 982).
- Channel maintenance: 4-person crew, bobcat, loader, dump truck, haul/disposal (8 hours) for a cost of \$4,500.
- Road maintenance at elevation above 983-984 [in addition to channel maintenance]: 4-person crew debris removal, equipment, street sweeper (4 hours) for a cost of \$1,000. Assume loader/dump truck are hired with channel maintenance.
- Road maintenance at elevation above 984-985 [in addition to channel maintenance]: 4-person crew debris removal, equipment, street sweeper (8 hours) for a cost of \$2,000. Assume loader/dump truck are hired with channel maintenance.
- Parking lot maintenance initiated at 984: 2- to 4- person crew, equipment, haul/disposal
- Unit costs:

4-person crew: \$100/hour

Bobcat: \$150/hour
Loader: \$150/hour
Dump Truck: \$150/hour
Street Sweeper: \$150/hour
Haul/Disposal: \$100 lump sum

Figure 3-11 and **Figure 3-12** show the damage and disruption components of the stressor cost function. The damages are expressed in dollars. The disruption is expressed as days the proportion of lanes were affected.

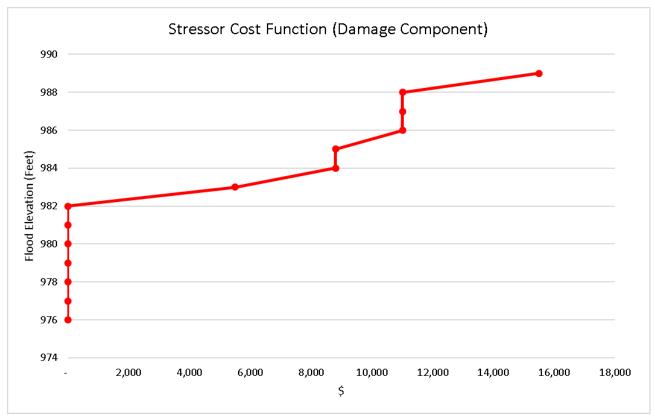


Figure 3-11. I-10 Stressor Cost Function, Damage Component



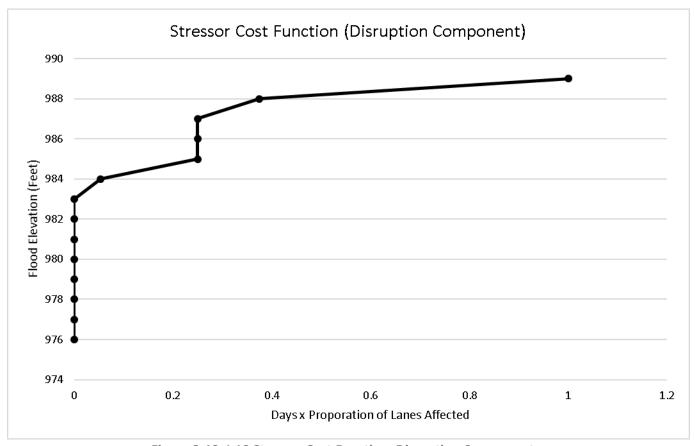


Figure 3-12. I-10 Stressor Cost Function, Disruption Component

Understanding how the disruption durations (shown in **Table 3-3**) impact the regional travel system and its users required following the process described in Section 2.5. Using these estimates and the outputs of the SBTAM analysis, the cost of a 24-hour closure of I-10 between North Haven and Milliken was calculated. **Table 3-4** shows the results for the base year model (2012) and the future year model (2040). The higher traffic volumes and congestion in 2040 result in much higher costs associated with a 24-hour closure compared to 2012. As a simplifying assumption given the project scope, these costs were linearly interpolated between these two years and linearly extrapolated after 2040. I-10 does have parallel routes, though its heavy travel volumes would cause considerable delays in the event of a closure.

Table 3-4. SBTAM 24-Hour Roadway Closure – Monetized Systemwide Impacts (2020 \$)

	2012	2040
Mileage Cost	\$13,299	\$44,837
Time Cost	\$1,426,432	\$3,090,249
Total Cost	\$1,439,730	\$3,135,086

The spreadsheet combines information from the stressor-cost function with stressor probability information. The annual climate projections input into this tool are the result of a Monte Carlo experiment, which generated 1,000 random simulations of annual maximum flows for each year and climate scenario. These simulations were generated based on the parameters of the climate projections for each year and climate scenario.





This spreadsheet structures the inputs, assesses the costs for each year, climate scenario, and simulation, and then estimates expected lifecycle costs under different climate scenarios for different alternatives. This information is then summarized as discounted present costs with percentile results. These percentile results help represent the uncertainty in the future conditions.

Figure 3-13 and **Figure 3-14** show the discounted lifecycle costs for each climate scenario. **Figure 3-13** shows costs associated with physical damage/maintenance only. **Figure 3-14** includes costs associated with physical damage/maintenance, incremental travel time costs, and incremental travel distance costs.

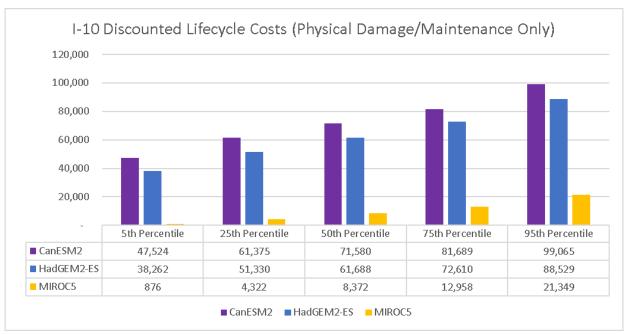


Figure 3-13. I-10 between North Haven and Milliken – Discounted Lifecycle Costs (Physical Damage Only) (2020 \$)

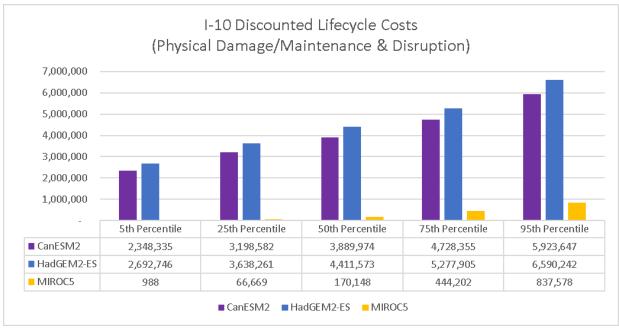


Figure 3-14. I-10 between North Haven and Milliken – Discounted Lifecycle Costs (Physical Damage/Maintenance and Disruption) (2020 \$)



Key findings include:

- Given its very high volume, a closure on I-10 between North Haven and Milliken would have a considerable impact on the regional transportation system. The time costs are much larger than the mileage (i.e., vehicle operating) costs.
- The flooding disruption costs outweigh the physical damage/maintenance costs. For the physical damage/maintenance only results, the 95th percentile simulation for all three climate scenarios had discounted lifecycle costs under \$100,000.
- For the combined damage and disruption costs, the results varied by climate model. For MIROC5, discounted lifecycle hazard costs were under \$1 million, even for the 95th percentile result. Results were similar for CanESM2 and HadGEM2-ES. For the 50th percentile, discounted lifecycle hazard costs were \$3.9 million for CanESM2 and \$4.4 million for HadGEM2-ES. Under the 95th percentile, costs were \$5.9 million for CanESM2 and \$6.6 million for HadGEM2-ES. For the damage-only results, CanESM2 had slightly higher discounted costs than HadGEM2-ES, presumably given the shape of the damage component of the stressor-cost curve along with the higher magnitude CanESM2 events in the middle of the century compared to HadGEM2-ES.
- Results are based on many simplifying assumptions and inputs. Methodology review and enhancement are needed to refine the inputs and analysis to ensure that results are reasonable.

3.9 Step 9: Evaluate Additional Considerations

Traffic analysis has been conducted to better understand the impact failed infrastructure can have on communities and local economies. The following sections present preliminary findings on potential impacts to various user groups, with a focus on low to moderate income populations and on commercial vehicles travelling through the project sites.

3.9.1 CHANGE IN COMMUTE TIME ACROSS USER GROUPS

Preliminary findings from the traffic analysis indicate low- to moderate-income users of the I-10 project site have slightly longer travel times during a closure scenario (highlighted in **Figure 3-15** and **Table 3-5**). The analysis showed these user groups would experience approximately three additional minutes of commute time in the base year (2012) and four minutes in a future year (2040), compared to two to three minutes for the base year and three to four minutes for future years for high-income commuters (household income over \$75,000). In addition, these workers are likely to have less flexible work schedules and therefore be more effected by these delays.





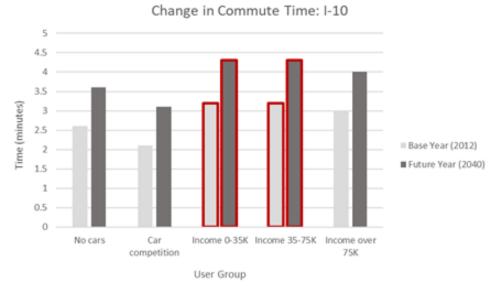


Figure 3-15. I-10 Closure Change in Commute Time Across User Groups

Table 3-5. Estimated Time Difference Between the Closure Scenarios and No-change Scenarios Across User Groups, in minutes.

	Base Year (2012)	Future Year (2040)
Change in Commute Time	I-10 (by ONT)	I-10 (by ONT)
No cars	2.6	3.6
Car competition	2.1	3.1
Income 0-35K	3.2	4.3
Income 35-75K	3.2	4.3
Income over 75K	3.0	4.0

Source: Cambridge Systematics, 2019.

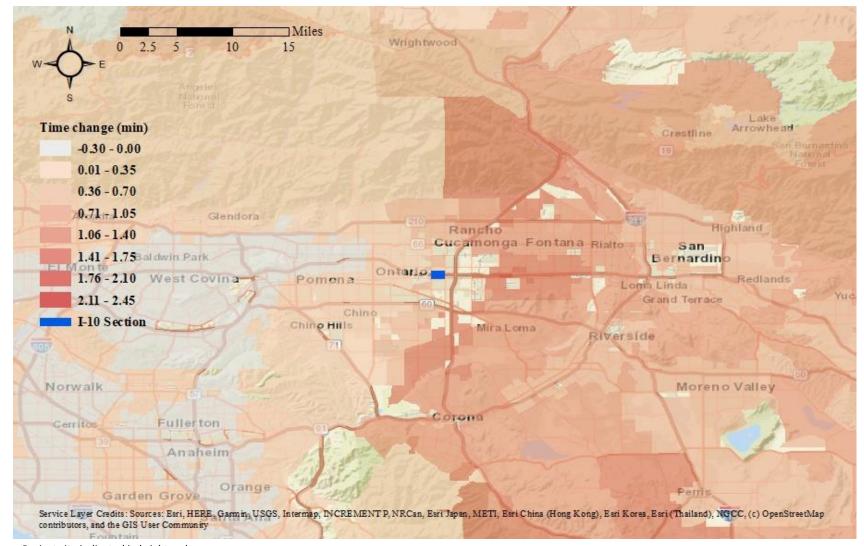
Definitions:

- 1. No Cars = Households with no vehicles (all income groups)
- 2. Car competition = Households with fewer vehicles than workers (all income groups)
- 3. Income 0-35K = Households with at least as many vehicles as workers (income USD 0-35K)
- 4. Income 35-75K = Households with at least as many vehicles as workers (income USD 35-75K)
- 5. Income over 75K = Households with at least as many vehicles as workers (income over USD 75K)
- 6. Note: Commute times are computed as the hypothetical commute time in vehicles regardless of mode taken. For the zero-auto households, commute times approximate additional delay on transit routes, where available.

Figure 3-16 and **Figure 3-17** show the variation of average commute times for all user groups across the region (not only those travelling through the project site). **Figure 3-18** shows the origin of low-income population trips to help public agencies and decision makers identify areas where special consideration may be required.





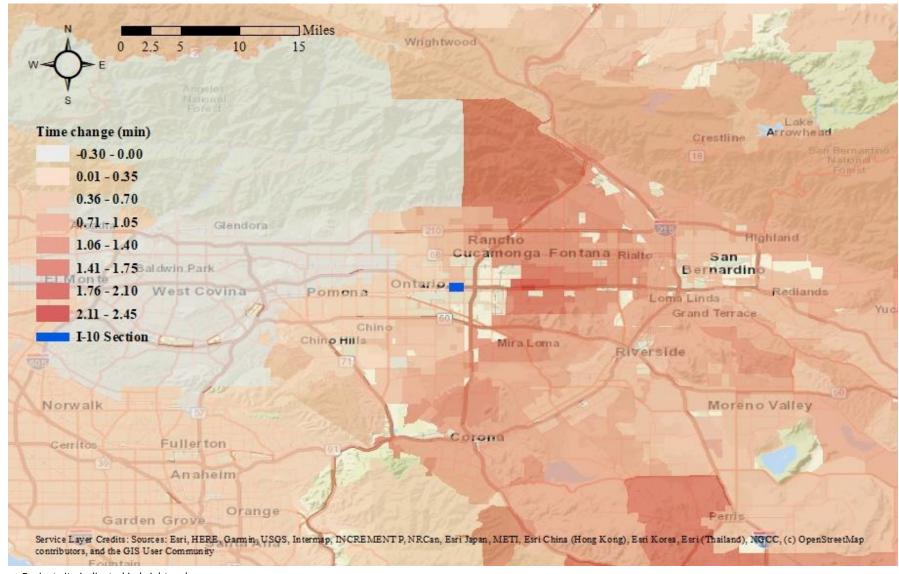


Project site indicated in bright red.

Figure 3-16. I-10 Average Commute Time Change (2012).





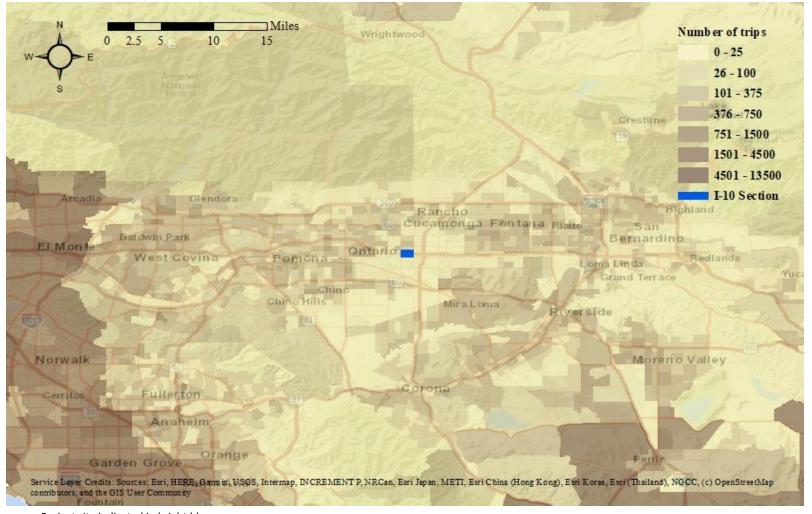


Project site indicated in bright red.

Figure 3-17. I-10 Average Commute Time Change (2040).







Project site indicated in bright blue.

Figure 3-18. I-10 Concentrations of Trip Origins for Low-Income Population.





As shown on the maps, areas with darker shades of red indicate longer average commute time change in the first two maps, which may be compared to the numbers of trips of low-income users. For the I-10 project site, there are several locations, particularly to the east of the project where both higher average commute times and higher number of trips of low-income households intersect. Further analysis is required to establish a relationship between the average commute time changes (for all trips) and the number of trips of low-income households. Establishing this relationship is key to identifying the areas where courses of action are needed to mitigate the negative travel time impacts on low income populations, who are disproportionately affected by a closure and with less resources to cope with the consequence of the closure.

3.9.2 CHANGE IN COMMERCIAL VEHICLE TRIP TIME

Reliable transportation routes are critical for supporting goods movement and economic activity. Commercial vehicles were analyzed for the potential impact that could occur if the project sites were closed. The preliminary analysis suggested the commercial vehicles along the I-10 route would experience delays lasting between two to three minutes. Further analysis on freight routes and flows of goods may be considered to better determine a course of action to mitigate any potential negative impact on commercial vehicles and the economy.

Table 3-6. Estimated Time Difference Between the Closure Scenarios and No-change Scenarios for Commercial Vehicles, in minutes.

	Base Year (2012)	Future Year (2040)
	I-10 (by ONT)	I-10 (by ONT)
Change in CV Trip Time	2.2	3.1
% Change in CV Trip Time	2.0%	2.4%

Source: Cambridge Systematics, 2019.

Note: Analysis considers all commercial vehicles that would normally use any of the removed links instead of all CVs that start or end in a defined study area. A review of trip-ends using the affected links shows a very large capture area, suggesting definition of a local study area would not be as meaningful as analysis of trips that would normally use the closed links.

3.10 Step 10: Select a Course of Action

This step involves evaluating the results of the analysis (Step 8) and additional considerations (Step 9) and making a decision about which action to take, whether it be no action or one of the adaptation options. Because adaptation options were not developed, this step was not completed.

3.11 Step 11: Develop a facility management plan

The analysis at this location indicates flooding in the area from heavy precipitation that may impact travelers, during heavy/severe rainfall in the area and the likelihood of such events may increase as climate-related hazards are predicted to increase. It will be important for Caltrans regional leaders to be aware of this area of concern if forecasts are predicting heavy rainfall, or as a location requiring monitoring during the event itself. The analysis presented in this work contains a range of uncertainties that are inherent to all climate-related technical analyses. Therefore, observation during any type of high precipitation event is recommended, particularly if wildfires were to occur in the drainage area, knowing that wildfire events contribute to increased run-off and debris and hence may exacerbate local conditions.

It should also be noted that the analysis conducted assumed that the drainage system would be operating at/near its capacity, a factor that is dependent on maintenance activity. Lack of maintenance can reduce system capacity and increase the likelihood of flood effects. A series of recommended maintenance activities are outlined next.

Recommendations for monitoring and maintenance:



- Inspect channel and culvert prior to rainy season and/or after every significant rainfall/runoff event.
- Video inspect culvert from entrance to exit on regular basis to assess condition and debris accumulation.
- Clear sediment and debris from channel and culvert entrance as necessary, especially after storm events to limit impacts to system capacity.

Recommendations for further analysis and remedial actions:

- For this location, conduct a more detailed hydrology and hydraulic analysis of culvert considering potential future increases in rainfall/runoff and the potential for flooding at this location.
- If needed, determine feasibility of increasing culvert capacity (e.g., adding another culvert) or improving entrance condition/opening to lower headwater and reduce localized flooding.





4. PILOT 2: INTERSTATE-15 AT CAJON PASS

4.1 Step 1: Understand the Site Context

The I-15 pilot assessment location is approximately 0.4 miles south of Cajon Junction (I-15 and Highway 138) along the southbound (west) side of I-15 in San Bernardino County. Cajon Wash is adjacent to the west side of the freeway in this location. This area is part of Cajon Pass, a heavily travelled pass between the San Bernardino and San Gabriel mountain ranges. The I-15 in Cajon Pass has experienced extreme weather in the past, including a heavy snowfall event that closed the road in December 2019²⁵, and a wildfire that also closed the road in addition to destroying vehicles and homes.²⁶

There are limited alternative routes to the Cajon Pass portion of I-15. The site is in Caltrans District 8. The 2016 Caltrans estimated Average Annual Daily Traffic (AADT) count for this segment of I-15 was 152,000.²⁷

Figure 4-1 and Figure 4-2 provide project vicinity and location maps. Figure 4-3 shows an aerial photo with terrain.

The FEMA Flood Insurance Rate Map (FIRM) shows this area as Flood Zone D (Areas of Undetermined Flood Hazard). **Figure 4-4** provides the existing floodplain limits as determined by a previous hydraulic study for Cajon Wash.

Figure 4-5 shows the United States Geological Survey (USGS) StreamStats watershed for Cajon Wash at this location.

²⁵ https://www.pe.com/2019/12/26/15-freeway-through-cajon-pass-closed-as-storm-rolls-through/

²⁶ https://www.mercurynews.com/2015/07/17/motorists-flee-as-wildfire-races-across-california-freeway/

²⁷ https://dot.ca.gov/-/media/dot-media/programs/traffic-operations/documents/census/aadt/tc-2016-aadt-volumes-a11y.pdf





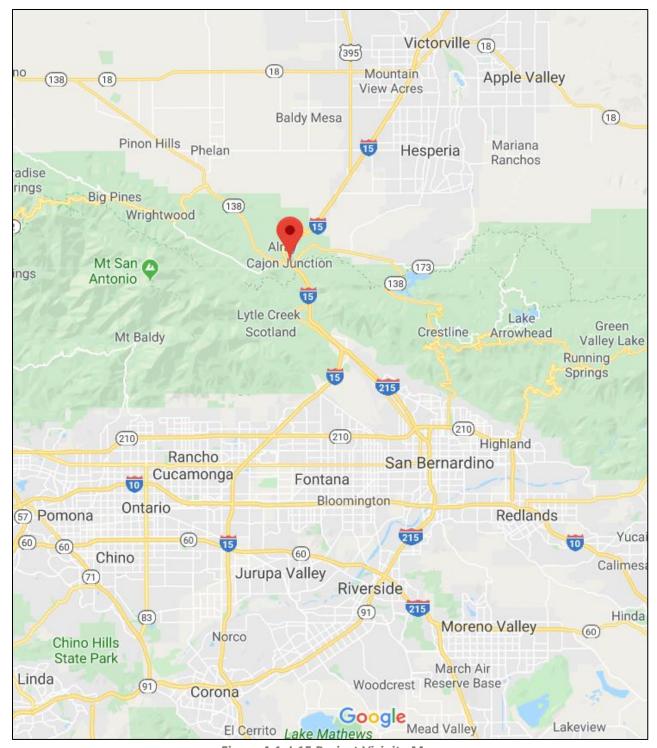
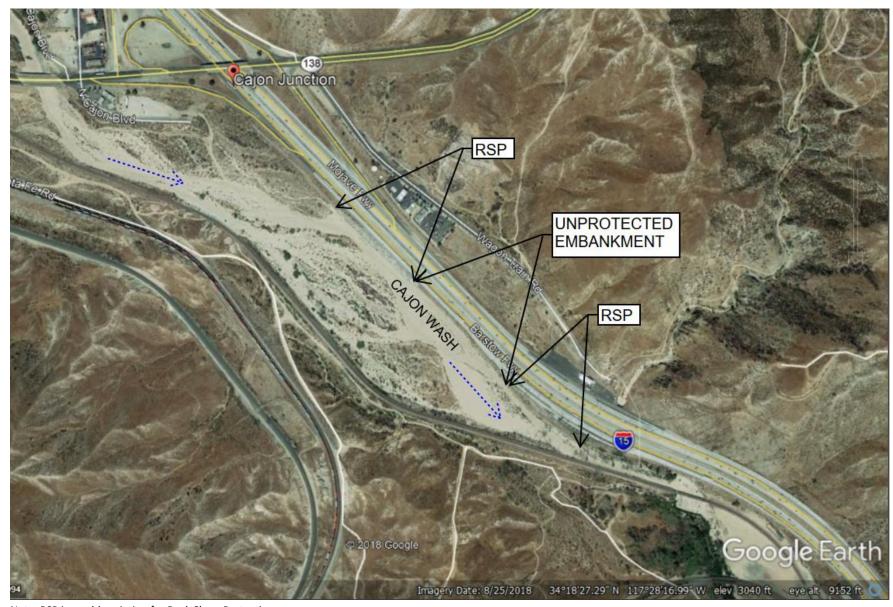


Figure 4-1. I-15 Project Vicinity Map







Note: RSP is an abbreviation for Rock Slope Protection

Figure 4-2. I-15 Project Location Map





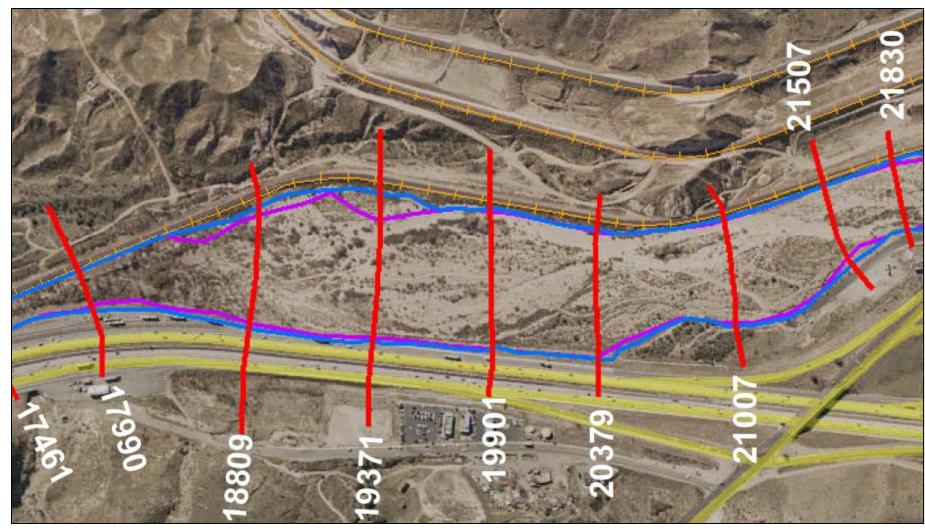
Imagery ©2019 Google, Landsat / Copemicus, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Data USGS, Data LDEO-Columbia, NSF, NOAA, Data CSUMB SFML, CA OPC, Data MBARI, Map data ©2019 200 ft

Source: Environmental Impact Statement/Environmental Impact Report for the Proposed BNSF Cajon Third Main Track Summit to Keenbrook, Environmental Technical Report, Hydrology and Hydraulic Impacts Analysis, 2005

Figure 4-3. Cajon Pass Section of I-15 Corridor – Aerial View with Exaggerated Terrain.







Note: Purple shows 10-year Floodplain limits and Blue Shows 100-Year Floodplain Limits. Red line show sections of the wash. White numbers show numbers of these cross sections from the hydraulic analysis; the numbers typically refer to the distance upstream or downstream from a certain feature, such as its headwater or confluence/estuary.

Figure 4-4. I-15 Cajon Wash Floodplain Map (10- and 100-year Floods)





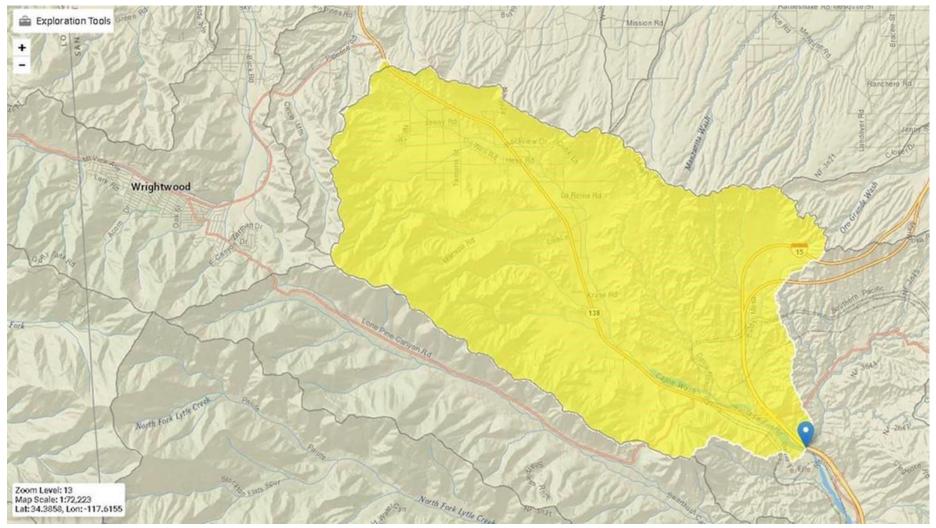


Figure 4-5. I-15 USGS StreamStats Watershed





4.2 Step 2: Document Existing or Future Base Case Facility

The existing facility was used for this pilot study. The highway is 10 lanes across (5 in either direction) at the Cajon Pass location.

This location was chosen for analysis for several reasons:

- The freeway elevation is relatively low in comparison with the adjacent wash (5 to 10 feet),
- A portion of the freeway embankment is unprotected (embankment areas immediately upstream and downstream are protected with rock slope protection [RSP]²⁸),
- Cajon Wash is an active channel with potential for main and sub-channel migration adjacent to the freeway embankment,
- Scour of the embankment or freeway flooding could impede traffic flows along this heavily utilized corridor.

The analysis focused on the unprotected portion of the embankment.

South of the pilot site, there is a project to construct tolled Express Lanes to relieve traffic congestion.

4.3 Step 3: Identify Climate Stressors

Precipitation (and the resulting stream flow) and wildfire are the primary environmental factors that both (1) affect the roadway and (2) are projected to increase in frequency and/or duration. This study covers both stressors, focusing how they influence future flood risk.

4.4 Step 4: Develop Climate Scenarios

Developing climate projections was not part of the scope of the pilots. Therefore, previously developed gridded²⁹ precipitation projections were used.

Data Source

These projections are from Global Climate Models (GCM) that had been downscaled by the Scripps Institute of Oceanography with a technique called Localized Constructed Analogs (LOCA)^{30,31}. Ten GCMs were identified by California State agencies as being representative of climate conditions across the state³². Three of these ten were used for the assessment.³³

Each model is typically run for different greenhouse gas emissions scenario to understand how emissions are likely to affect the climate. The projections used for this pilot corresponded to one emissions scenario called

²⁸ Rock slope protection is an erosion prevention strategy that involves placing rock along a slope to help stabilize it.

²⁹ Gridded means that the projections are given in a grid of rectangles corresponding with different geographic coordinates. Each rectangle has its own projection.

³⁰ http://loca.ucsd.edu/

³¹ Projections were originally downloaded from the Cal-Adapt Data Server: http://albers.cnr.berkeley.edu/data/scripps/loca/

³² http://www.water.ca.gov/climatechange/docs/2015/Perspectives Guidance Climate Change Analysis.pdf.

³³ The models used are: CanESM2, HadGEM2-ES, and MIROC5.



Representative Concentration Pathway 8.5 (RCP 8.5)³⁴. This emissions scenario assumes that emissions will continue to rise through the end of this century³⁵.

Data Processing

These projections had been previously processed further using the following steps:

- Annual Maxima Series (AMS)³⁶ were derived for each climate scenario.
- Generalized Extreme Value distributions (GEVs) were fit to four 30-year time slices of the AMS for each climate scenario: 1976-2005, 2010-2039, 2040-2069, and 2070-2099.
- These distributions were used to estimate precipitation values corresponding to the 2-, 5-, 10-, and 25-year events.
- Percentage changes between backcasted values (i.e., 1976-2005) and forecasted values were calculated.
- For each climate scenario, percentage changes were applied to the National Oceanic and Atmospheric Administration (NOAA) Atlas 14³⁷ precipitation values for the applicable return periods. NOAA Atlas 14 estimates are based on observed historical data.
- Given the relatively small sample of 30 years for each modeled time slice, percentage changes for 25-year events were applied to 50-, 100-, 200-, and 500-year events from NOAA Atlas 14.
- Drainage basins upstream of the analysis location were delineated using the USGS StreamStats³⁸ tool. **Figure 3-5** depicts the watershed.
- Finally, area-weighted mean (AWM) precipitation estimates were developed for the drainage basin using the gridded projections.

Recommended Improvements

The following recommended improvements to this methodology should be included in future risk assessments. The pilot projects had a limited scope and therefore, these practices were not included.

- More than one emissions scenario should be used.
- A larger set of GCMs should be used.
- Rather than assuming stationarity for each 30-year period, the GEVs should be fit with a time parameter to account for non-stationarity.
- Projections should be tested for bias and biases should be corrected as needed.
- Confidence intervals should be developed for each set of projections and for NOAA Atlas 14 estimates.
- Percentage changes from 25-year events should not be assumed to apply to other events.

³⁴ The term Representative Concentration Pathway (RPC) refers to one of the emissions scenarios developed by the Intergovernmental Panel on Climate Change. It is a time series of emissions and concentrations of greenhouse gases in the atmosphere. For more information, see: https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html.

³⁵ https://cal-adapt.org/tools/

³⁶ Annual Maxima Series refers to a series that contains the maximum daily precipitation event from each year.

³⁷ NOAA Atlas 14 contains precipitation data (derived from historical observations) for locations across the United States:

https://hdsc.nws.noaa.gov/hdsc/pfds/pfds map cont.html

³⁸ https://streamstats.usgs.gov/ss/





Resulting Climate Projections

Figure 4-6 shows the watershed precipitation depth frequency curves for a 24-hour duration event. **Figure 4-7** shows the temporal change in the 10-year/24-hour precipitation depth for each climate scenario alongside the historical depth from NOAA Atlas 14.

There is substantial variation between the projections, including between the models and between the timeframes within each model. For example, the HadGEM2-ES 2070-2099 projections are higher than other projections. This variation can be partially attributed to the substantial uncertainty regarding future extreme precipitation events and due to the methodology used. The integration of the recommendations previously listed are therefore important to reduce part of the observed variation. Using the estimated projections is still helpful as a stress test of climate conditions to the facility.

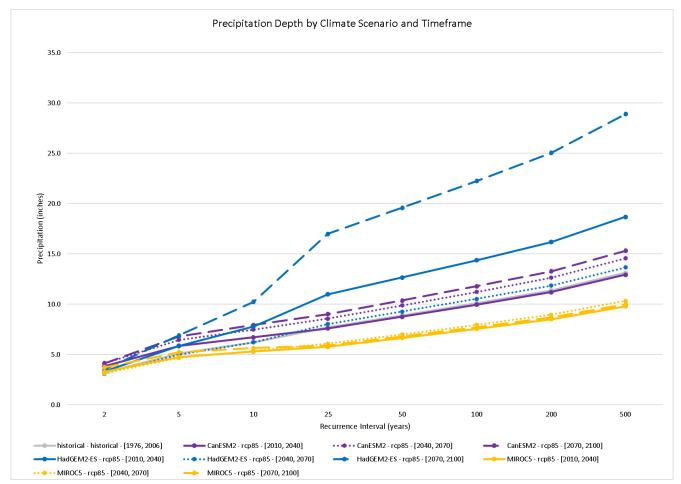


Figure 4-6. Cajon Wash Drainage Basin - Precipitation Depth Frequency Curves (24-Hour Duration), RCP 8.5





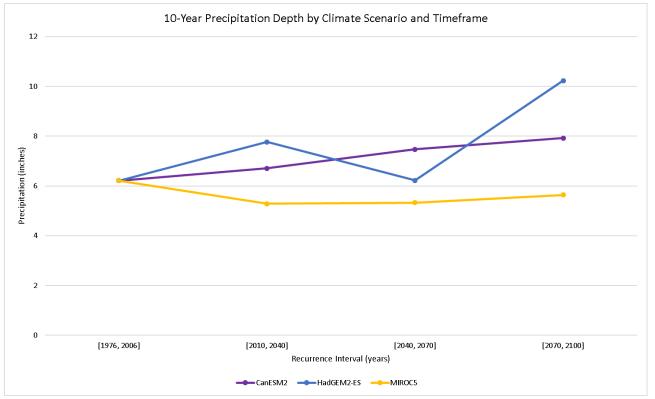


Figure 4-7. Cajon Wash Drainage Basin - Precipitation Depth 10-Year Event (24-Hour Duration), RCP 8.5

4.5 Steps 5: Assess Performance of the Facility

Assessing the performance of the facility requires hydrologic and hydraulic assessments. A hydrologic assessment can be used to estimate peak flows given the precipitation projections. In turn, a hydraulic assessment can be used to estimate flood elevations given the peak flow projections.

4.5.1 HYDROLOGY

The USGS StreamStats program was utilized to delineate the watershed of Cajon Wash at the analysis location. The USGS StreamStats watershed delineation and basin characteristics were used to estimate 25-, 50-, 100-, 200-, and 500-year return period peak flows based on historical data.

While using a hydrologic model of the watershed near the facility to forecast future peak flows is recommended, due to the limited scope of the pilot studies, hydrologic modeling was not conducted. Instead, future peak flows were estimated by scaling the historical peak flows based on the relationship between historical precipitation and future precipitation.





Table 4-1. Unadjusted Peak Flows

	Return Frequency							
Scenario	25-year (cfs)	50-year (cfs)	100-year (cfs)	200-year (cfs)	500-year (cfs)			
Historical	4,426	6,414	8,720	11,531	15,453			
CanESM2 [2010, 2040]	4,235	6,157	8,398	11,113	14,968			
CanESM2 [2040, 2070]	5,815	8,242	11,158	14,267	19,121			
CanESM2 [2070, 2100]	6,607	9,281	12,408	15,795	21,168			
HadGEM2-ES [2010, 2040]	10,604	14,327	18,595	23,671	31,723			
HadGEM2-ES [2040, 2070]	4,917	7,065	9,589	12,517	16,775			
HadGEM2-ES [2070, 2100]	26,143	34,919	45,323	57,694	77,319			
MICROC5 [2010, 2040]	1,876	2,901	4,161	5,695	8,117			
MICROC5 [2040, 2070]	2,223	3,353	4,781	6,505	9,175			
MICROC5 [2070, 2100]	2,003	3,068	4,400	5,997	8,512			

4.5.2 WILDFIRE

Fire affects the hydrology of clear-water runoff in several ways, including "changes to evapotranspiration, interception, infiltration, surface, and sub-surface soil moisture storage, and surface and sub-surface flow paths". Decreased watershed lag times and higher peak flows are caused by loss of vegetation, litter, and duff and resulting in lowering of overland, rill and channel flow friction coefficients.³⁹

Sediment/debris bulking factors and procedures used by southern California counties (i.e., Los Angeles, Ventura, San Bernardino, Riverside, Orange, and San Diego), the Los Angeles District of the U.S. Army Corps of Engineers, Federal Emergency Management Agency (FEMA), and the Interagency Burned Area Emergency Response (BAER) Team were reviewed for use in this study to account for the effects of wildfire on the estimated peak flows.

With stream gage data, published gage heights and peak discharges already include flow bulking, and can be considered bulked, as well as flood frequency results using these data. However, the potential effects of wildfire increase the clear water peak flow and the amount of sediment/debris in the flow.

The FEMA method was utilized in this study to account for the potential effects of wildfire on the estimated peak flows. As part of FEMA's effort to assess the 2003 post-fire flood hazards, several flooding sources throughout San Diego, San Bernardino, Riverside, Ventura, and Los Angeles Counties were identified for analysis. The recommended increase in bulking due to both a burned surface condition and an increase in sediment/debris is given by the following equation:

Qfinal peak= Qpre-burn x Clear water Adjustment Factor x Bulking Adjustment Factor

The clear water adjustment factors are provided in **Table 4-2**. Note that the FEMA adjustment factors assume a condition immediately after a fire. A high burn was assumed to occur over a quarter of the 25.6 square mile watershed. A composite or adjusted clear water adjustment factor of 1.4 was calculated which accounts for partial watershed burn $[(6.4 \text{ mi2} \times 2.62 + 19.2 \text{ mi2} \times 1.0/(26.2 \text{ mi2})=1.41]$.

³⁹ Sediment/Debris Bulking Factors and Post-Fire Hydrology for Ventura County (Draft 2011)



Table 4-2. Post-Burn Clear Water Adjustment Factors

Burn Condition	Post-fire Adjustment Factor (Burn Severity Factor)
Unburned/Very Low Burn	1.00
Low Burn	1.76
Moderate Burn	2.20
High Burn	2.62

Estimated sediment bulking factors are then applied to the adjusted peak discharges. FEMA recommended post-burn bulking adjustment factors for 5- to 100-year design storms are provided in **Table 4-3**. The values for the 100-year storm were utilized for 25- to 500-year storm flows in this analysis. A bulking factor of 1.1 was utilized for this study.

Table 4-3. Post-Fire Sediment Bulking Factors

	Sediment Bulking Factor					
Area (mi²)	5-Year Storm Event	100-Year Storm Event				
0-3	1.5	1.4				
3-10	1.3	1.2				
Above 10	1.2	1.1				

The resulting combined increase in estimated peak flows utilized was $1.41 \times 1.1 = 1.55$. **Table 4-4** shows the final burned/bulked peak flow estimates.

Table 4-4. Burned/Bulked Peak Flows

	Return Frequency						
Scenario	25-year (cfs)	50-year (cfs)	100-year (cfs)	200-year (cfs)	500-year (cfs)		
Historical	6,861	9,942	13,515	17,873	23,953		
CanESM2 [2010, 2040]	6,565	9,544	13,017	17,224	23,200		
CanESM2 [2040, 2070]	9,013	12,775	17,295	22,115	29,637		
CanESM2 [2070, 2100]	10,241	14,386	19,232	24,482	32,810		
HadGEM2-ES [2010, 2040]	16,436	22,207	28,823	36,691	49,171		
HadGEM2-ES [2040, 2070]	7,621	10,950	14,862	19,401	26,001		
HadGEM2-ES [2070, 2100]	40,521	54,125	70,250	89,426	119,845		
MICROC5 [2010, 2040]	2,908	4,497	6,449	8,827	12,581		
MICROC5 [2040, 2070]	3,445	5,198	7,410	10,083	14,221		
MICROC5 [2070, 2100]	3,104	4,755	6,820	9,296	13,194		





4.5.3 HYDRAULICS

To determine flood elevations for each of the historical and future peak flows at the analysis location the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) software was utilized to calculate peak flood elevations along Cajon Wash near the analysis location. Hydraulic cross section data (channel geometry and roughness coefficients) were taken from the 2005 HEC-RAS analysis included in the Hydrology and Hydraulic Impacts Analysis portion of the Environmental Impact Statement/Environmental Impact Report for the Proposed BNSF Cajon Third Main Track Summit to Keenbrook. Cross sections between Highway 138 on the north and the weigh station on the south were utilized for this analysis.

The method in the Los Angeles County Department of Public Works Sedimentation Manual was utilized to estimate potential scour depths along the unprotected embankment adjacent to Cajon Wash⁴⁰. This method is typically used to determine top down depths for rock riprap embankment/levee design. The method estimates total expected scour based on several scour components. The total estimated scour is given by the following equation:

Ztotal = Zdeg + Zgs + Zls + Zbs + Zi + 1/2h

Where: Ztotal = Total potential vertical adjustment along embankment

Zdeg = Long-term degradation (assumed negligible for this study)

Zgs = General scour (from LACDPW Sedimentation Manual Appendix C-3)

Zls = Local scour (not utilized for embankment analysis)

Zbs = Bend scour (from LACDPW Sedimentation Manual Appendix C-9)

Zi = Low-flow incisement (used 2.0 for this analysis)

H = Bed form height (from LACDPW Sedimentation Manual Appendix C-9)

Table 4-5 provides flood elevations at cross section 18809. **Table 4-6** provides scour depths at cross section 18809. Note that overtopping of the freeway embankment begins at elevation 3,015', but a median barrier contains flows to the southbound lanes up to elevation 3017.5'. **Figure 4-8** through **Figure 4-10** provide graphs of the data in these tables.

Table 4-5. Flood Elevations at RAS Section 18809

	Return Frequency							
Scenario	25-year (ft)	50-year (ft)	100-year (ft)	200-year (ft)	500-year (ft)			
Historical	3011.89	3012.31	3012.71	3013.14	3013.67			
CanESM2 [2010, 2040]	3011.85	3012.27	3012.66	3013.08	3013.60			
CanESM2 [2040, 2070]	3012.20	3012.64	3013.08	3013.51	3014.09			
CanESM2 [2070, 2100]	3012.35	3012.80	3013.26	3013.71	3014.31			
HadGEM2-ES [2010, 2040]	3013.00	3013.51	3014.03	3014.55	3015.41			
HadGEM2-ES [2040, 2070]	3012.00	3012.43	3012.85	3013.27	3013.82			
HadGEM2-ES [2070, 2100]	3014.80	3015.63	3016.28	3016.96	3019.58			
MICROC5 [2010, 2040]	3011.20	3011.51	3011.83	3012.16	3012.62			
MICROC5 [2040, 2070]	3011.31	3011.63	3011.97	3012.33	3012.79			
MICROC5 [2070, 2100]	3011.24	3011.56	3011.88	3012.23	3012.68			

⁴⁰ Given the scope of the analysis, the protected portion of the embankment was not analyzed.



Table 4-6. Scour Depths at RAS Section 18809

		Return Frequency						
Scenario	25-year (ft)	50-year (ft)	100-year (ft)	200-year (ft)	500-year (ft)			
Historical	7.4	8.0	8.8	10.6	11.6			
CanESM2 [2010, 2040]	7.3	8.0	9.6	10.5	11.7			
CanESM2 [2040, 2070]	7.8	8.1	12.4	13.5	14.0			
CanESM2 [2070, 2100]	8.0	9.9	11.4	11.7	13.0			
HadGEM2-ES [2010, 2040]	10.3	11.5	13.0	13.4	18.7			
HadGEM2-ES [2040, 2070]	7.6	9.2	10.1	11.2	12.2			
HadGEM2-ES [2070, 2100]	17.0	19.7	20.4	20.6	22.8			
MICROC5 [2010, 2040]	4.8	6.7	7.2	7.8	8.8			
MICROC5 [2040, 2070]	5.7	6.9	8.6	8.0	9.0			
MICROC5 [2070, 2100]	4.2	6.6	7.1	7.5	9.4			

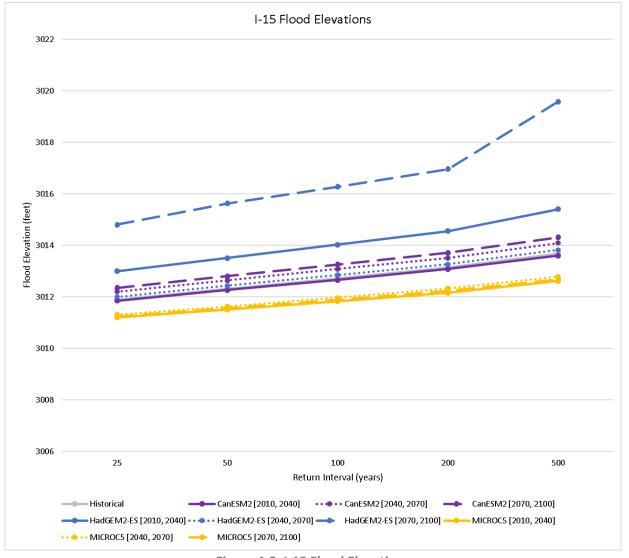


Figure 4-8. I-15 Flood Elevations



Figure 4-9 and **Figure 4-10** show the cross section of the creek at the analysis location with water surface elevations and scour depths/limits.

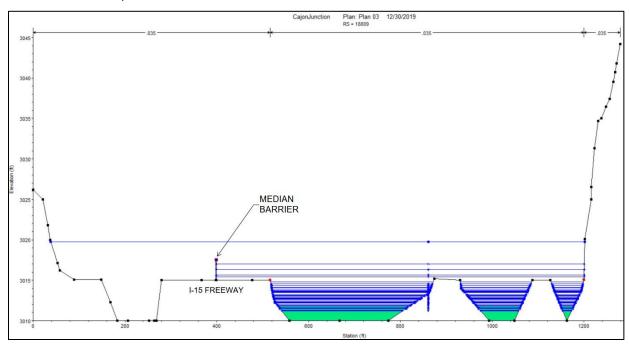


Figure 4-9. I-15 HEC-RAS Cross Section 18809 Flood Elevations

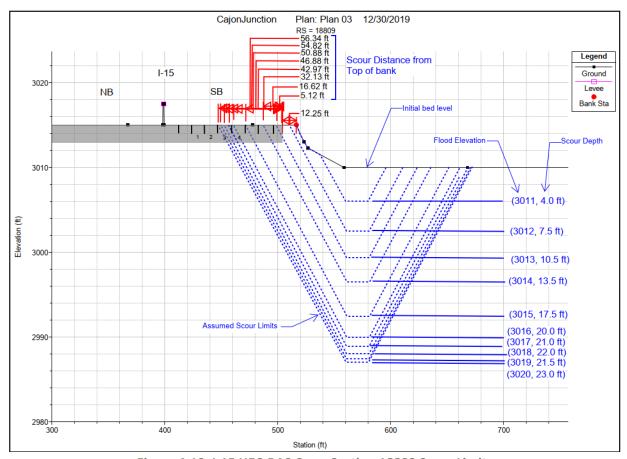


Figure 4-10. I-15 HEC-RAS Cross Section 18809 Scour Limits





4.6 Step 6: Develop Adaptation Options

This step involves developing strategies to address the climate-related risk posed to the asset. These can include design, operational, maintenance, policy, or other measures. They are often referred to as adaption options. While developing adaptation options was not part of the pilot assessment scope, the next phase of this project will develop and assess adaptation options for different locations.

4.7 Step 7: Assess Performance of Adaptation Options

This step involves assessing the performance of the adaptation options developed in Step 6. It applies an analysis like the one conducted in Step 5 to each adaptation option to understand how the option address the climate risk in comparison with the baseline 'no action' option. While assessing adaptation options was not part of the pilot assessment scope, the next phase of this project will assess the performance of adaptation options for different locations.

4.8 Step 8: Conduct an Economic Analysis

For the economic analysis, lifecycle climate hazard costs were estimated at the facility under the different climate scenarios. The lifecycle cost analysis is documented in a spreadsheet that accompanies the deliverable. Because adaptation options were not developed as part of the pilot assessment, only the base case facility was analyzed. When multiple adaptation options are analyzed, capital, operations, and maintenance costs should be included along with costs related to the probable occurrence of climate hazard events. With this additional information, the economic analysis can be used to measure the cost effectiveness of the different action alternatives.

The spreadsheet was used to calculate expected cumulative costs to the asset over time. To do this, it uses curves relating flood elevations to their probabilities (from Step 5) and flood elevations to their costs incurred (stressor-cost function). Every time a facility is flooded, costs are calculated per the stressor-cost function and summed for all such events over time. Due to the limited scope of the pilot assessment, it was assumed that the asset is not improved when damage does occur. This assumption is unlikely to hold when damage costs are high and there are feasible options for mitigating the impacts. **Table 4-7** shows some of the basic inputs to the lifecycle cost analysis. The spreadsheet documents these inputs in greater detail, as well as other assumptions.

Input	Value
Real Discount Rate	3%
Analysis Start	1/1/2020
Analysis End	1/1/2100
Value of Time (VOT)	27.20 2015\$/hour
Light Duty Vehicle Operating Costs (VOC)	0.39 2017\$/mile
Commercial Truck VOC	0.90 2017\$/mile

Table 4-7. Lifecycle Cost Analysis Basic Inputs

Costs accounted for in the analysis include physical damage repair costs, incremental travel time costs, and incremental travel distance costs. **Table 4-8** shows the stressor-cost function for the location.⁴¹ It provides physical damage in 2019\$ terms and disruption durations in days.

⁴¹ Weigh station impacts are excluded from the lifecycle cost assessment.





Table 4-8. I-15 Stressor Cost Function

Flood Elevation (feet)	Flow Magnitude (cfs)	Physical Damage & Repair Cost	Flooding Days Disruption	Scour Repair Days Disruption	Travel Lane Flooding	Scour Depth (feet)	Scour Impact/ Damage	Notes	Total Lanes	Flood Lanes Affected	Scour Lanes Affected
-	-	0	0	0	None	-	none	No travel impacts	10	0	0
3011	-	0	0	0	None	4	minor embankment loss	No travel impacts	10	0	0
3012	4,917	724,400	0	0	None	8	embankment loss to top of bank - add RSP	No travel impacts	10	0	0
3013	10,604	812,700	0	0	None	11	Embankment and outside shoulder loss	No travel impacts	10	0	0
3014	16,775	1,012,700	0	0	None	14	Bank, shoulder, weigh station access	Weigh station out of service	10	0	0
3015	26,143	1,231,800	0	0	None	18	Bank, shoulder, weigh station access	Weigh station out of service	10	0	0
3016	34,919	1,417,100	0.5	45	SB - all lanes (0.5 day)	20	Bank, shoulder, weigh station access, outside lane	Weigh station and outside lane out of service	10	5	1
3017	57,694	1,548,700	1	60	SB - all lanes (1 day)	21	Bank, shoulder, weigh station access, 2 outside lanes	Weigh station and two outside lanes out of service	10	5	2
3018	57,694	1,596,700	2	60	SB/Northbo und (NB) - all lanes (2 day)	22	Bank, shoulder, weigh station access, 2 outside lanes	Weigh station and two outside lanes out of service	10	10	2



Flood Elevation (feet)	Flow Magnitude (cfs)	Physical Damage & Repair Cost	Flooding Days Disruption	Scour Repair Days Disruption	Travel Lane Flooding	Scour Depth (feet)	Scour Impact/ Damage	Notes	Total Lanes	Flood Lanes Affected	Scour Lanes Affected
3019	57,694	1,629,500	2	60	SB/NB - all lanes (2 day)	23		Weigh station and two outside lanes out of service	10	10	2
3020	77,319	1,653,500	2	60	SB/NB - all lanes (2 day)	23		Weigh station and two outside lanes out of service	10	10	2





Table 4-9 shows how the physical damage and repair estimates were developed. For each elevation, the number of units was multiplied by the applicable unit costs. Then, each cost component was tallied into a total repair cost for each elevation.

Table 4-9. Physical Damage Costs by Elevation

	Demo/ Disposal	2- ton Rock Slope Protection	Concrete Barrier	Import Fill	Road	Total
Unit Cost	\$10	\$110	\$100	\$20	\$11	
Units	cubic yards	cubic yards	linear feet	cubic yards	square feet	
Elevation	# Units by Elevation					Cost
3011′	0	0	0	0	0	\$0
3012′	0	6040	600	0	0	\$724,400
3013′	386	6040	600	1580	4800	\$812,700
3014′	1157	6040	600	5915	14400	\$1,012,700
3015′	1640	6040	600	13330	20400	\$1,231,800
3016′	2170	6040	600	18700	27000	\$1,417,100
3017′	2749	6040	600	21030	34200	\$1,548,700
3018′	2749	6040	600	23430	34200	\$1,596,700
3019′	2749	6040	600	25070	34200	\$1,629,500
3020′	2749	6040	600	26270	34200	\$1,653,500

Figure 4-11 and **Figure 4-12** show the damage and disruption components of the stressor cost function. The damages are expressed in dollars. The disruption is expressed as days times the proportion of lanes affected.



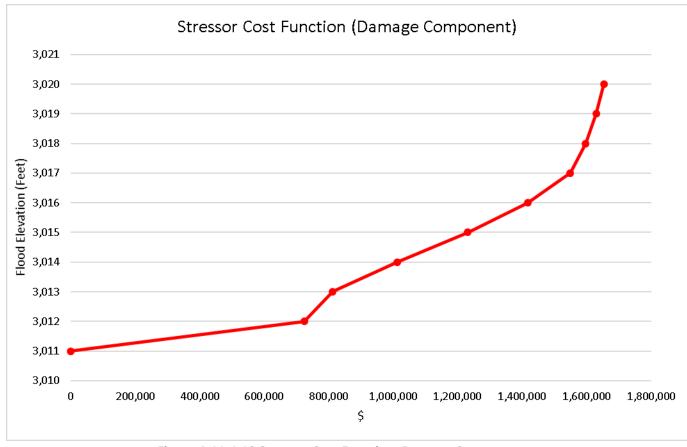


Figure 4-11. I-10 Stressor Cost Function, Damage Component





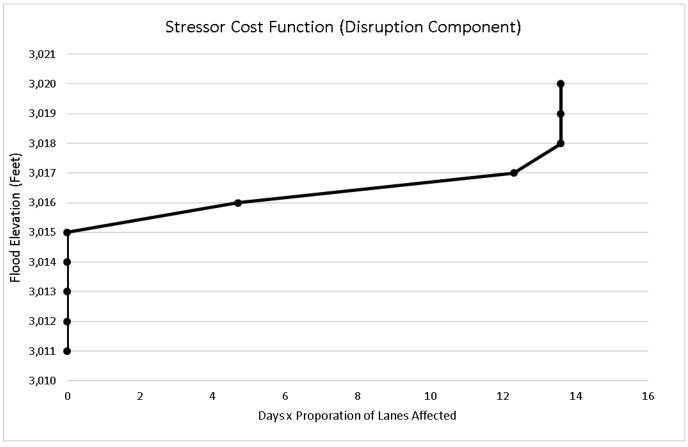


Figure 4-12. I-10 Stressor Cost Function, Disruption Component

Understanding how the disruption durations (shown in **Table 5-8**) impact the regional travel system and its users required following the process described in Section 2.5. Using these estimates and the outputs of the SBTAM analysis, the cost of a 24-hour closure of I-15 in Cajon Pass was calculated. **Table 4-10** shows the results for the base year model (2012) and the future year model (2040). The higher traffic volumes and congestion in 2040 result in much higher costs associated with a 24-hour closure compared to 2012. Given the lack of parallel routes and heavy volume, the disruption costs are very high at this facility. The time cost represents most of the overall costs.

Table 4-10. SBTAM 24-Hour Roadway Closure - Monetized Systemwide Impacts (2020 \$)

	2012	2040
Mileage Cost	\$3,595,777	\$5,549,646
Time Cost	\$26,817,254	\$73,640,911
Total Cost	\$30,413,030	\$79,190,556

The spreadsheet combines information from the stressor-cost function with stressor probability information. The annual climate projections input into this tool are the result of a Monte Carlo experiment, which generated 1,000 random simulations of annual maximum flows for each year and climate scenario. These simulations were generated based on the parameters of the climate projections for each year and climate scenario.

This spreadsheet structures the inputs; assesses the costs for each year, climate scenario, and simulation; and then estimates expected lifecycle costs under different climate scenarios for different alternatives. This



information is then summarized as discounted present costs with percentile results. These percentile results help represent the uncertainty in the future conditions.

Figure 4-13 and **Figure 4-14** show the discounted lifecycle costs for each climate scenario. **Figure 4-13** shows costs associated with physical damage/maintenance only. **Figure 4-14** includes costs associated with physical damage/maintenance, incremental travel time costs, and incremental travel distance costs.

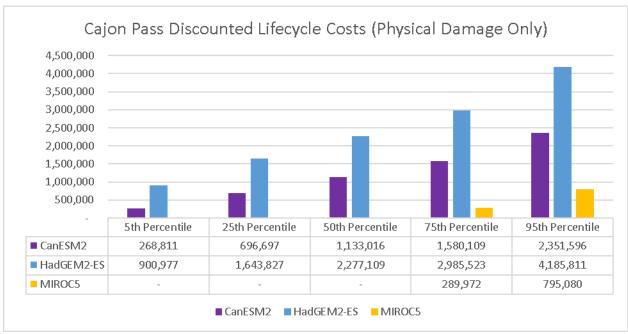


Figure 4-13. Cajon Pass – Discounted Lifecycle Costs (Physical Damage Only) (2020 \$)

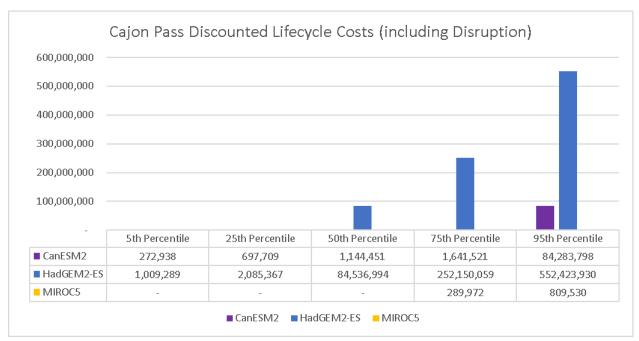


Figure 4-14. Cajon Pass – Discounted Lifecycle Costs (Physical Damage/Maintenance and Disruption) (2020 \$)





Key findings include:

- Given its high volume and lack of redundant routes, an I-15 closure would likely have a massive impact on the regional transportation system, creating substantial time delays and vehicle operating costs. The time costs (based on Value of Time costs from FHWA) are much larger than the mileage (i.e., vehicle operating) costs.
- Based on historical conditions, an I-15 closure due to Cajon Wash flows is very unlikely. A historical 500-year peak flow is not expected to close the roadway.
- The results varied widely by climate model, particularly for the analysis that included disruption costs in addition to physical damage costs. For MIROC5, no climate hazard lifecycle costs were projected under the 50th percentile result. Even under the 95th percentile result, hazard lifecycle costs were relatively low. Discounted lifecycle costs were also relatively low for CanESM2, with \$1.1 million under the 50th percentile and \$1.6 million under the 75th percentile. However, discounted costs were over \$84 million for the 95th percentile. HadGEM2-ES had much higher discounted lifecycle costs, with \$85 million for the 50th percentile and \$552 million for the 95th percentile.
- For the results with high lifecycle costs, these costs are primarily attributable to scour of the roadway. The
 delay associated with lane closures to repair scour damage drive the costs much more than the physical
 damage repair itself.
- Results are based on many simplifying assumptions and inputs. Methodology review and enhancement are needed to refine the inputs and analysis to ensure that results are reasonable.

4.9 Step 9: Evaluate Additional Considerations

Traffic analysis has been conducted to better understand the impact failed infrastructure can have on communities and local economies. The following sections present preliminary findings on potential impacts to various user groups, with a focus on low- to moderate-income populations and on commercial vehicles travelling through the project sites.

4.9.1 CHANGE IN COMMUTE TIME ACROSS USER GROUPS

Preliminary findings from the traffic analysis indicate low- to moderate-income users of the I-15 (Cajon Pass) project site have slightly longer travel times during a closure scenario (highlighted in **Figure 4-15** and **Table 4-11**). This is presumably due to these trips having longer distances or traversing more congested roadways. The analysis showed that those who rely on the Cajon Pass could experience severe delays of three to four hours. The pattern is also true for populations who do not have access to a car and instead rely on transit and other modes for commuting. Those modes of transportation are using the same alternate routes as those used by private vehicles to reach their destinations, and therefore, are subject to comparable delays. In addition, these workers are likely to have less flexible work schedules and therefore be more effected by these delays.

⁴² Costs are not incurred until elevation exceeds 3012'. Only the 200- and 500-year events exceeded 3012' for MIROC5 in each of the timeframes analyzed.



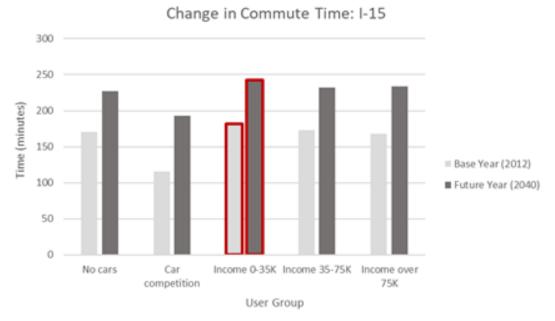


Figure 4-15. I-15 Closure Change in Commute Time Across User Groups

Table 4-11. Estimated time difference between the closure scenarios and no-change scenarios, in minutes.

	Base Year (2012)	Future Year (2040)	
Change in Commute Time	I-15 (Cajon Pass)	I-15 (Cajon Pass)	
No cars	170.3	227.1	
Car competition	115.3	192.6	
Income 0-35K	181.4	242.9	
Income 35-75K	172.7	231.9	
Income over 75K	168.3	234.0	

Source: Cambridge Systematics, 2019.

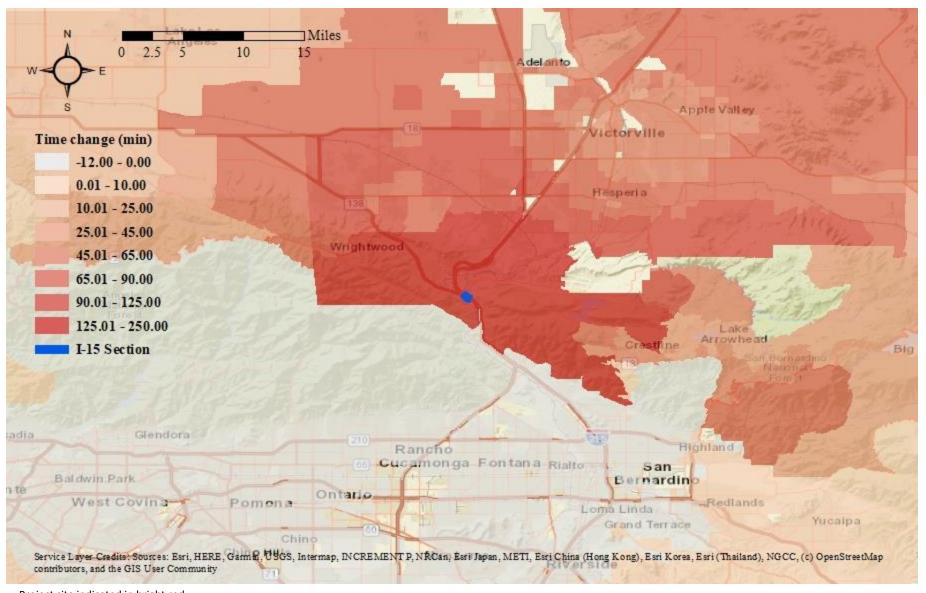
Definitions:

- 1. No Cars = Households with no vehicles (all income groups)
- 2. Car competition = Households with fewer vehicles than workers (all income groups)
- 3. Income 0-35K = Households with at least as many vehicles as workers (income USD 0-35K)
- 4. Income 35-75K = Households with at least as many vehicles as workers (income USD 35-75K)
- 5. Income over 75K = Households with at least as many vehicles as workers (income over USD 75K)
- 6. Note: Commute times are computed as the hypothetical commute time in vehicles regardless of mode taken. For the zero-auto households, commute times approximate additional delay on transit routes, where available.

Figure 4-16 and **Figure 4-17** show the variation of average commute times for all user groups across the region (not only those travelling through the project site). **Figure 4-18** shows the origin of low-income population trips to help public agencies and decision makers identify areas where special consideration may be required.





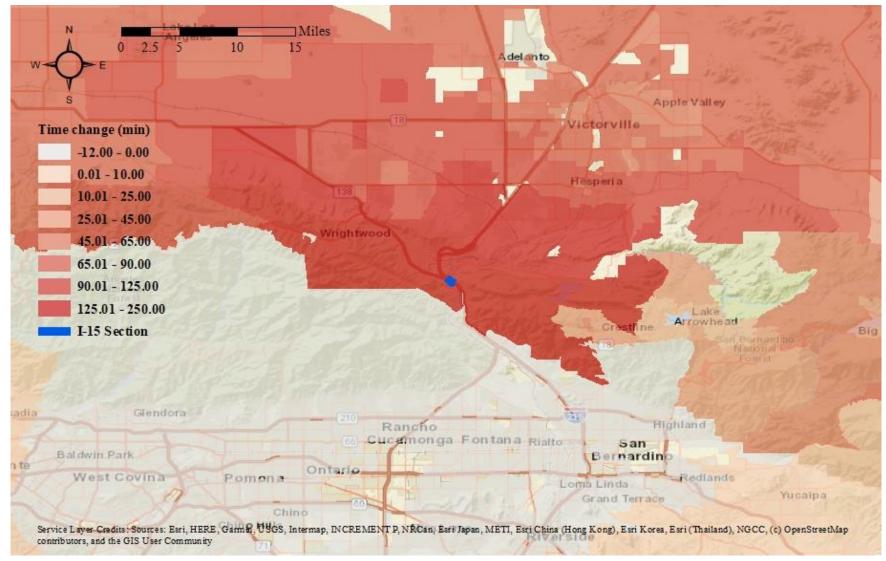


Project site indicated in bright red.

Figure 4-16. I-15 Average Commute Time Change (2012).





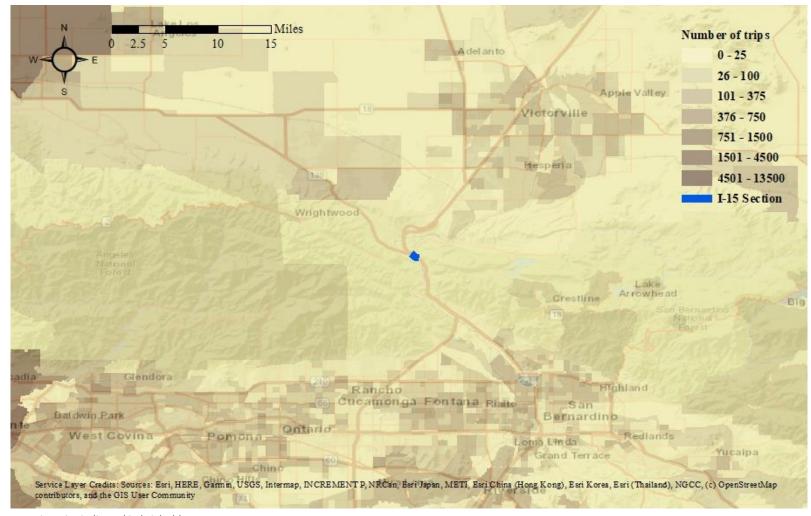


Project site indicated in bright red.

Figure 4-17. I-15 Average Commute Time Change (2040).







Project site indicated in bright blue.

Figure 4-18. I-15 Concentrations of Trip Origins for Low-Income Population



As shown on the maps, areas with darker shades of red indicate longer average commute time change in the first two maps, which may be compared to the numbers of trips map of low-income users. For the I-15 project site, there are several locations, particularly to the north and northeast of the project where both higher average commute times and higher number of trips of low-income households intersect. Further analysis is required to establish a relationship between the average commute time changes (for all trips) and the number of trips of low-income households. Establishing this relationship is key to identifying the areas where courses of action are needed to mitigate the negative travel time impacts on low-income populations, who are disproportionately affected by a closure and with less resources to cope with the consequence of the closure.

4.9.2 CHANGE IN COMMERCIAL VEHICLE TRIP TIME

Reliable transportation routes are critical for supporting goods movement and economic activity. Commercial vehicles were analyzed for the potential impact that could occur if the project sites were closed. The preliminary analysis suggested the commercial vehicles travelling through the Cajon Pass would experience over an hour worth of delay. Further analysis on freight routes and flows of goods must be considered given the significant impact a closure through the I-15 Cajon Pass could have in disruption to goods movement. This analysis would be used to better determine a course of action to mitigate the potential negative impact commercial vehicles and the economy may face.

Table 4-12. Estimated Time Difference Between the Closure Scenarios and No-change Scenarios for Commercial Vehicles, in minutes.

	Base Year (2012) I-15 (Cajon Pass)	Future Year (2040) I-15 (Cajon Pass)
Change in CV Trip Time	72.3	80.9
% Change in CV Trip Time	43.4%	45.5%

Source: Cambridge Systematics, 2019.

Note: Analysis considers all commercial vehicles that would normally use any of the removed links instead of all CVs that start or end in a defined study area. A review of trip-ends using the affected links shows a very large capture area, suggesting definition of a local study area would not be as meaningful as analysis of trips that would normally use the closed links.

4.10 Step 10: Select a Course of Action

This step involves evaluating the results of the analysis (Step 8) and additional considerations (Step 9) and making a decision about which action to take, whether it be no action or one of the adaptation options. Because adaptation options were not developed, this step was not completed.

4.11 Step 11: Develop a facility management plan

The analysis at this location indicates flooding in the area from heavy precipitation that may impact travelers, during heavy/severe rainfall in the area – particularly on the westbound lanes where flooding from the adjacent creek could occur – and the likelihood of such events may increase with projected increases in the frequency and duration of rainfall and wildfire events. It will be important for Caltrans regional leaders to be aware of this area of concern if forecasts are predicting heavy rainfall, or as a location requiring monitoring during the event itself. The analysis presented in this work contains a range of uncertainties that are inherent to all climate-related technical analyses. Therefore, observation during any type of high precipitation event is recommended, particularly if wildfires were to occur in the drainage area, knowing that these events contribute to increased runoff and debris and hence may exacerbate local conditions.





The technical analysis for this project assumed that stream embankments are maintained and there are no points of incursion or scour at the base, which may cause sliding and reduction of protection in this area. There are a few actions recommended for this area.

Monitoring and maintenance of existing mitigation strategies:

- Inspect the creek embankment in the area prior to rainy season after storm events producing flows in wash, including:
 - checking for embankment surficial erosion and scour at toe of slope;
 - repairing surface rills and gullies on embankment and repair toe as needed; and
 - installing marked posts at upstream and downstream ends of unprotected portion of embankment to assist water and scour level estimates.

Additional analysis and appropriate remedial actions:

- Design and construct engineered rock slope protection within unprotected or under-protected portions of embankment.
- Evaluate replacement of the current metal beam guard rail with a concrete barrier at edge of the shoulder to provide increased freeway flood protection for the road during events.



5. CONCLUSION AND LESSONS LEARNED

The effects of projected increases of climate-related hazards on society are going to be wide-ranging. Mobility and the transportation system will be impacted, including both transportation infrastructure exposed to increased weather-related stresses and system users, who rely on that infrastructure and could experience more travel delays, income loss and other consequences. Such users include commuters, freight companies, local businesses, and community residents.

Appropriate consideration of the potential impacts of climate-related hazard changes requires a perspective of looking forward to identify how conditions may change and hence to design these systems effectively. This perspective represents a shift from traditional practice, which historically has looked to the past (observed rainfall/wildfire/landslide events) to guide decisions. Appropriate planning for the consideration of projected future climate-related hazard events includes understanding the physical and system risks and considering them in the larger context of appropriate investment strategies that maximize public benefits.

The testing of how the FHWA-developed ADAP method could be employed in the context of the I-10 and I-15 projects, as described in previous pages, determined its applicability in project development for projects in the region. Importantly for this test, available resources were used to generate the metrics required for input. ADAP was suggested as a good candidate approach for climate -sensitive project development because of its use of available data and information, while also recognizing the uncertainties in projected future conditions.

WRCOG and SBCTA, with the conduct of this work, have undertaken a process to identify the best methods for risk-based decision-making into asset-level decisions. This pilot effort, conducted for two critical system assets in the region, identified resources available to determine potential consequences and converted those consequences into quantified metrics (dollar value), and identified other measures to consider such as the delay costs imposed on disadvantaged populations for whom transportation system impacts represent a higher proportional cost.

The following conclusions can be drawn from this work. These recommendations can influence later phases of the work and support the implementation of additional regional and local studies.

- A risk-based engineering assessment requires several analyses to provide the information and data needed for design. For example, detailed studies (e.g., hydrology/hydraulic) and feedback from civil engineers on potential impact to facilities/roads/bridges are required. These studies are best completed with the accepted engineering processes in place, where changing climate conditions can be inserted in the place of other climate data used for design (e.g., rainfall). Ongoing projects in the planning phase/conceptual design phase are a good place to introduce these methods into the region.
- Conducting analyses of this type allows for the identification of risks to the transportation system and leads to a more robust dialogue on how to best invest limited resources. The documentation of future climate conditions and how they may impact the system physically and systematically can provide good information on how best to proceed with the design of any capital investment project in the region. Implementing processes such as this yields a wealth of data points and information to help guide decision making.
- The SBTAM model incorporates metrics important for considering system effects and reflects policies identified in legislative requirements for the State of California. These include:
 - changes in VMT/VHT data to support investment decisions,
 - delays of freight/goods movement to determine potential impacts on businesses,
 - GHG emissions to satisfy environmental requirements, and
 - impacts on users by income class to safeguard an equitable development.





- Assigning costs to system users in the region will vary depending on the location of the roadway within
 the regional network. The results of this analysis show that the system could absorb short closures of I-10
 due to additional system capacity/travel options, but the closure of I-15 near Cajon Pass would impose
 significant system impacts. This conclusion should be considered for any future investment in this corridor.
 Other tests of system resilience can be useful to inform any phase of project evolution (e.g., LRTP, project
 development).
- Future capital project decisions should be supported by a similar assessment process to provide a full suite
 of information/data with which design teams can advance their recommended strategies. Methods for
 generating needed input data could become a part of environmental review, preliminary design and final
 design processes so that designs are both resilient to long-term change and cost-effective.

Overall, the methods tested and tools used in this application show promise in advancing resilience strategies in the region. As WRCOG and SBCTA look to apply this approach further in the next phase of the project, there are several recommendations for improving it and making it more scalable for the region:

- Materials and documentation need to be accessible to both technical professionals (such as designers) but also to planners and community leaders. In some cases, two versions will be needed one for a more general audience and one for a more technical audience. Engagement with both audiences is needed to understand usability of this approach and how it can be scaled.
- Analysis of common adaptation measures in addition to only do-nothing costs. Many lessons about costs and cost effectiveness of adaptation options will be transferable from one asset location to another.
- More comprehensive inclusion of transportation system impacts on different types of households and income levels; on emissions; and on freight travel. This can be done with the development of a few simple metrics that are easy to understand.
- Decisions about project design typically require at least some detailed, site-specific analysis. In these
 cases, methods like ADAP cannot be automatically scaled to all locations within the region. However, there
 are several ways in which this methodology can be made more transferable to other locations and easier
 to use. They include:
 - A tool that automatically conducts the transportation system impacts assessment with the local travel demand models without requiring expertise on how to run the model or contractor time.
 - A set of future climate projections suitable for project level design and decision making for common applications (such as H&H analysis or pavement design).
 - A lifecycle cost analysis tool (somewhat similar to the spreadsheet delivered with this pilot, but that is much more user friendly).
- As noted above, ongoing projects in the planning phase/conceptual design phase are a good place to introduce these methods into the region. Ample time should be included to coordinate with local agencies and their contractors in order to gather the data needed.
- There are several recommendations throughout this report for relatively minor technical improvements. This
 section will not restate all these improvements here, but they include specific improvements on how climate
 projections are developed (Step 5), how H&H analyses are performed with these climate projections (Step 5),
 how the transportation system impact using the travel demand model is incorporated into the overall analysis
 (Step 8), and how the lifecycle cost analysis is performed (also Step 8).

The development of these tools and processes will make it easier to address climate risk at the project level and make the overall system more resilient. This type of capability would provide benefits to the region moving forward as climate-related hazard events increase in frequency and intensity, creating new challenges and stresses to communities and to the infrastructure that supports them.